

An Abstract of the Thesis of

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Title: Optimization and Control of Cable Deployment Systems

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An optimization methodology, algorithms, and computer program for cable/lumped-body deployment system are developed for the design and installation of sonar packages in deep ocean ranges. In addition, a methodology and algorithms for the control of the system are proposed.

A penalty function is developed in terms of the system parameters and the dynamic constraints are set up for the optimization of cable/lumped-body deployment system. Deployment procedures and segmentations characterized by their initial and terminal condition are proposed. Alternating Direction (ADM) and Modified Alternating Direction (MADM) methods are employed for the optimum search. The optimization algorithms are then implemented on a desk-top computer. The objective of the search is to achieve the optimum vessel speed and cable pay-out rate that result in the minimum penalty value.

Numerical examples are presented to test the robustness of the algorithm (ADM) and the compute program capabilities. The results are compared to those of the MADM method and the entire space search.

During actual installation, it is anticipated that randomness in the excitation will

cause sonar packages to miss the exact target locations. Thus a continuous correction in the controllable parameters is necessary. Three alternative types of control algorithms are presented for these reasons.

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Deployment Systems**

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Typed by _____ Mohamed Mtira

Dedicated to my mother Rabha,
my father Rejeb,
my brothers Bassim and Abdelhakim,
and my sister Lobna

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OPTIMIZATION AND CONTROL OF CABLE DEPLOYMENT SYSTEMS

CHAPTER 1 INTRODUCTION

1.1 Background

The Naval Civil Engineering Laboratory (NCEL) as part of its effort in the Advanced Ocean Ranges (AOR) project is committed to the improvement of the U.S. Navy's capability to design and install general purpose underwater ranges at arbitrary sites. The key to that improvement lies in the development of computer simulation techniques for optimization and active control of cable/lumped-body installation technology and of identification of key parameters in the design/installation of such systems. Given an optimum acoustic design of a deep ocean range, it is necessary to evaluate the design of both the hardware and the installation procedure to ensure the most expeditious installation of the system for satisfactory performance over the expected lifetime of the system.

A typical scenario for installation of a deep ocean range is a sequential pay-out from a surface vessel of several single cables with discrete nodes spaced at appropriate lengths along the cable such that the nodes are positioned along an irregular path on an irregular sea floor. Minimization of the installation cost and/or time is a prime consideration while satisfying specified tolerances in the location of the installed nodes and structural integrity of the system. The optimum sequences of vessel headings and speeds and of pay-out velocities are sought within the constraints dictated by the site

conditions, cable and equipment characteristics and the acoustic design. Having designed an optimum installation procedure considering all the dynamic loading conditions at the sites, one must still anticipate unexpected environmental and vessel changes which cause nodes to deviate from the predicted optimum trajectories. Corrective actions must be instituted to return the nodes to a path leading to bottom placement with acceptable tolerances. Control action must be evaluated to prevent over-correction of subsequent nodes in the system. Procedures are needed to identify key parameters in the design and installation of ranges by comparison of "real" and simulated results under irregular sea conditions that can be expected at the sites. That identification will lead to selection of those parameters most critical in the control of the system installation. The "real" results mentioned above may be experimental results or results observed from laying one or more lines of nodes immediately prior to the line being deployed.

The terminology and algorithms to build a suite of computer programs to design and install cable/lumped-body system already exist. However, existing programs are intended for analysis of well-posed problems with accurate descriptions of loading conditions and system characteristics, rather than for interactive design and control of systems to achieve optimum performance.

1.2 Previous Studies

Research was conducted at Oregon State University under the auspices of the Office of Naval Research to develop a dynamic response simulation method for cable/lumped-body systems. A FORTRAN program named KBLDYN was developed

by Chiou for modeling the three-dimensional nonlinear dynamic behavior of such systems (Chiou, 1989). In that work, the nonlinear static and dynamic analysis of three dimensional, singly-connected cable-mass systems is presented. Nonlinearities of the system include large displacements, material characteristics, non-conservative fluid loadings, and interactions of the cable and the interconnected masses.

The solution algorithm in KBLDYN employs an implicit time integration method which allows large time steps to be used without degradation in solution accuracy. This reduces computational time drastically. Once the implicit method is used, the problem is transformed into an equivalent "static" two-point nonlinear boundary-value problem along the cable length at every time instant. A semi-analytical method is presented to solve those equations by direct integration without use of large matrices or matrices equation solvers.

The numerical method and computer program (KBLDYN) developed by Chiou have been validated for representative problems by comparing solution accuracies and computation times with other solution methods and experimental results. It has been selected as the base model for the dynamic response simulation program of AOR. However, for some problems, difficulties in convergence and overflow due to rapid growth of the extraneous solutions and singularities in the governing equations were encountered. Numerical damping and drift, which may lead to inaccurate predictions of long term response, were also noticed. These problems were later rectified by Sun (1992) using a combination of an error suppression method, a stable Newmark-like implicit integration scheme, and special treatment of the boundary conditions.

1.3 Objective

The objective of this study is to develop a methodology, algorithms, and computer programs for the optimization of cable/lumped-body deployment systems in deep waters using existing programs (KBLDYN), and to develop a methodology and algorithms for the control of the systems. It is achieved by performing the following tasks:

- 1) Set up the dynamic constraints and develop a mathematical expression of a penalty function for the cable installation procedure.
- 2) Develop algorithms for the optimization of the penalty function to determine the optimum vessel and pay-out speeds for the installation of the sonar packages on the sea floor.
- 3) Develop a computer program based on the algorithms and using KBLDYN program to search for the optimum vessel and pay-out speed values in the installation operations.
- 4) Run a planned series of cable/body deployment examples to test the robustness of the algorithm and the computer program capabilities.
- 5) Set up a control logic for the cable/lumped-body deployment system and define the control parameters.
- 6) Develop control algorithms to correct the deviations occurring in the dynamic state of the system due to randomness in the excitation by continuously regulating the controllable parameters.

1.4 Scope

In this study, a methodology, algorithms, and computer programs for the optimization of cable/lumped-body deployment systems are developed. Also a methodology and algorithms for the control of the systems are proposed.

In chapter 2, the general concept of optimization is introduced. The objective of optimization, definitions of the cost/penalty function and constraints are delineated. A presentation and a brief description of the most applied optimization algorithms and techniques are summarized.

The cable/lumped-body system and optimization procedures are described in detail in chapter 3. Operation constraints and the penalty function are set up. Initial and terminal configurations with deployment procedures are examined. Two optimization algorithms to search for the optimum controllable values to minimize the installation cost of the deployment operations in calm water are presented.

A series of examples to demonstrate the capability and efficiency of the developed algorithms and computer programs are given in chapter 4.

In chapter 5, an introduction to control theory is presented accompanied with suggested control algorithms that can be applied to control the installation process of cable/lumped-body system in presence of waves and currents.

Chapter 6 contains conclusions and recommendations to improve KBLDYN program to facilitate the use of the control algorithms. Potential extensions of the optimization algorithms to multiple bodies and to include vessel heading in the computer programs are also discussed.

CHAPTER 2 SURVEY OF OPTIMIZATION METHODOLOGIES

2.1 Perspective

Optimization studies how to mathematically describe and attain what is optimum (maximum or minimum). The theory encompasses the quantitative study of optima and methods for finding them (Beightler, et al., 1979). The role that optimization plays in the solution of problems can be stated as follows: After constraints that must be satisfied by the problem solution are defined, all significant forms of solutions which satisfy the constraints should be conceived; and from the generally infinite number of such solutions, the one which is best under some criteria of goodness should be extracted by using optimization principles (Donald, 1969). Given a specific measure of performance (called cost or penalty function) and a specific set of constraints, one can designate a system as optimum (with respect to the performance measure and the constraints) if it "performs" as well as or better than any other system which satisfies the constraints.

2.2 Objectives

The objective of optimization for any problem investigated is the improvement of the system. Normally a multitude of solutions can be found to any problem, and it is therefore necessary to choose the "optimum" solution for a given problem. Prior to determining the optimum solution, it is necessary to formulate the objective of the study mathematically in terms of an objective function to provide a quantitative basis for comparison.

2.3 Statement of a Problem

An optimization problem can be stated as follows (Rao, 1979).

Find $X = (x_1, x_2, \dots, x_n)^T$ which minimizes $P(X)$ subject to the constraints

$$g_i(x) \leq 0, i = 1, 2, \dots, m$$

and

$$l_i(x) = 0, i = m+1, m+2, \dots, p$$

where X is an n -dimensional vector (the superscript T indicates transposition), $P(X)$ is the objective function (or cost function) and $g_i(X)$ and $l_i(X)$ are, respectively the inequality and the equality constraints. The number of variables n and the number of constraints p need not be related. For p equal to zero, there are no constraints, and the problems are called unconstrained optimization. Those problems for which p is greater than zero are known as constrained optimization problems (Rao, 1979).

2.3.1 Cost function

The cost function measures the penalty that must be paid as a consequence of the dynamic system's trajectory. The "cost" may indicate deviation from some ideal physical situation and be expressed in engineering units; or it simply may represent the passage of time in going from initial to final values of the state. A positive "cost" could be considered a negative "benefit," or vice versa (Stengel, 1986).

2.3.2 Constraints

Constraints are relationships that must be satisfied. They limit the set of solutions from which an optimal solution is to be found. Constraints can either be equalities or

inequalities. Equality constraints require that some function of variables be maintained at a constant value throughout the solution interval, and inequality constraints prohibit a function of variables from exceeding some limit during the trajectory of the system (Stengel 1986).

2.4 Approaches

A few commonly used analytical and numerical optimization approaches including classical techniques, linear, dynamic and nonlinear programming are briefly described in this section.

2.4.1 Classical Techniques

The classical methods of optimization are useful in finding the optimum of continuous and differentiable functions. These methods are analytical and make use of the techniques of differential calculus in locating the optimum points (Rao, 1979).

The optimization of continuous functions subjected to equality constraints can be stated as:

$$\begin{aligned} \text{Minimize } P &= P(X) \text{ subject to} \\ g_i(X) &= 0, \quad i = 1, 2, \dots, m \\ &\quad m \leq n \\ \text{where} \quad X &= (x_1, x_2, \dots, x_n)^T \end{aligned}$$

Method of Direct Substitution

This method of solution is to solve the m restrictions simultaneously for m of the n variables. These may then be substituted into the objective function. This will

produce a new objective function,

$$P = P(x_1, x_2, \dots, x_{n-m})$$

in terms of a reduced number of variables which are no longer subject to the equality restrictions (Rao, 1979).

Method of Constrained Variation

The basic idea used in this method is to find a closed form expression for the first order differential of $P(DP)$ at all points at which the constraints $g_i(X) = 0$, $i = 1, 2, \dots, m$ are satisfied. The desired optimum points are then obtained by setting the differential dP equal to zero (Rao, 1979).

The Method of Lagrange Multipliers

Both methods described above are based on the principle of eliminating m variables by making use of the constraints and then solving the problem in terms of the remaining $n-m$ variables. In the Lagrange multiplier method, one additional variable is introduced to the problem for each constraint. Thus if the original problem has n variables and m equality constraints, m additional variables are added to the problem so that the final number of unknowns becomes $n+m$ (Rao, 1979).

2.4.2 Linear Programming

Linear programming is an optimization method applied for the solution of problems in which the objective function and the constraints appear as linear functions

of the variables. The constraints equations in a linear programming problem may be in the form of equalities or inequalities. A linear programming problem is often stated in the following standard form:

Find $X = (x_1, x_2, \dots, x_n)^T$ which minimizes

$$f(X) = \sum_{i=1}^n c_i x_i$$

subject to the constraints

$$\sum_{k=1}^n a_{jk} x_k = b_j, \quad j = 1, 2, \dots, m$$

and

$$x_i \geq 0, \quad i = 1, 2, \dots, n$$

where c_i, a_{jk} and b_j are constants.

One way to find the optimal solution of the given linear programming problem is to generate all the basic solutions and pick the one which is feasible and corresponds to the optimal value of the objective function. This can be done because the optimal solution, if one exists, always occurs at an extreme point or vertex of the feasible domain (Beveridge and Schechter, 1970).

The Simplex Method is often used to reduce the effort required to solve any linear programming problem. If the solution is not optimal, the method provides for finding a neighboring basic feasible solution which has a lower or equal value of the objective function. The process is repeated (a finite number of times) until an optimum is found.

2.4.3 Dynamic Programming

For some problems, decisions have to be made sequentially at different points in time or space, at different levels and at a number of stages (thus called sequential and/or multistage decision problems). Dynamic programming is a mathematical technique well suited for the optimization of multistage decision problems. The technique decomposes a multistage decision problem into a sequence of single stage decision problems which are easier to solve than the original problem. Multistage decision problems can also be solved by the direct application of the classical optimization techniques. However, this requires the number of variables to be small, the functions involved to be continuous and continuously differentiable, and the optimum points not lie at the boundary. Further, the problem has to be relatively simple so that the resulting equations can be solved either analytically or numerically. Nonlinear programming techniques can be used to solve slightly more complicated multistage decision problems. But their application requires the variables to be continuous and *a priori* knowledge about the region of the global minimum or maximum (Beveridge and Schechter, 1970).

Unlike other programming techniques, dynamic programming has no standard mathematical formulation for the optimization procedures. Depending on the conditions prescribed for the system, a dynamic programming problem can be solved as an initial- or as a final-value problem.

2.4.4 Nonlinear Programming

In general the objective and constraint functions are nonlinear. Nonlinear programming problems can be classified as unconstrained and constrained problems.

Unconstrained Nonlinear Programming

An unconstrained optimization problem can be stated as: Find X such that $P(X)$ is minimum.

Several methods are available for solving an unconstrained optimization problem. These methods can be classified into two broad categories as direct search methods and descent methods (Table 2.1, see Rao (1979)).

The direct search methods require only objective function evaluations and do not use the partial derivatives of the function in finding the minimum and hence are often called nongradient methods. These methods are most suitable for simple problems involving a relatively small number of variables, and are, in general, less efficient than the descent methods, which require, in addition to function evaluations, the evaluation of the first and possibly higher order derivatives of the objective function. The descent techniques (which use the derivatives or gradient of the penalty function) are also known as gradient methods (Rao, 1979).

<u>Direct search</u> (Derivative of the function not required)	<u>Descent</u> (Derivatives of the function required)
(i) Random search	(i) Steepest descent
(ii) Univariate	(ii) Conjugate gradient
(iii) Pattern search	(iii) Newton's
(iv) Rosenbrock's rotating coordinates	(iv) Variable metric
(v) Simplex method	

Table 2.1 Unconstrained Minimization Methods.

Constrained Nonlinear Programming

A constrained nonlinear programming problem can be stated in the standard form as: Find X such that $P(X)$ is minimum and $g_i(X) \leq 0 \quad i = 1, 2, \dots, m$.

There are many techniques available for the solution of a constrained nonlinear programming problem. All these methods can be classified into two broad categories, namely, the direct methods and indirect methods as shown in Table 2.2 (Rao, 1979). In the direct methods, the constraints are handled in an explicit manner whereas in most of the indirect methods, the constrained problem is solved as a sequence of unconstrained minimization problems (Rao, 1979).

<u>Direct methods</u>	<u>Indirect methods</u>	
(i) Heuristic search	(i) Transformation of variables	
(ii) Constraint approximation	(ii) Penalty function	
(iii) Methods of Feasible directions	Interior	Exterior
(a) Zoutendijk's		
(b) Gradient projection		

Table 2.2 Constrained Minimization Methods.

CHAPTER 3 OPTIMIZATION OF CABLE/LUMPED-BODY

DEPLOYMENT SYSTEMS

3.1 Physical System

The physical cable/lumped-body system consists of five major components: the tow vessel, cables, lumped bodies, target locations and the environment. Each of these components can be characterized as follows.

3.1.1 Tow Vessel

The tow vessel can be characterized by its size, weight/displacement, turn radius and power output. With this information and the initial location of the vessel, the instantaneous and maximum allowable displacements, velocities and accelerations may be determined along with their maximum allowable changes. The allowable magnitudes and changes in velocity and acceleration also depend on the cable pay-out and the number and position of the lumped bodies submerged in the water column. The vessel is assumed to be an ideal energy source, that is, its operation (position and velocity) can be perfectly regulated and is not influenced by the dynamic state of the cable/lumped-body system.

3.1.2 Cables

The towed cables may be characterized by their size, shape, material and method of construction, mass per unit length, submerged length, and maximum length. With this

information and a description of the cable configurations in the water column, the maximum allowable stresses, cable flexibility, maximum curvatures, dead loads may be determined. The fluid loads also depend on the cable pay-out and the environment. It is assumed that there is always sufficient amount of cable for all deployment scenarios considered for optimization.

3.1.3 Lumped Bodies

The properties of the lumped bodies are the number, size, shape, type, wet weight, mass, hydrodynamic characteristics and spacing along the cable of the bodies. These variables will influence maneuverability of the tow vessel, constraints on pay-out rates, cable loadings, and feedback systems based on pinger locations.

The lumped bodies are assumed to be sufficiently heavy and the frictional force coefficient between the lumped bodies and the sea floor is assumed to be sufficiently large that the positions of the lumped bodies are fixed once they reached the sea floor. It is assumed that no sliding of the lumped bodies along the sea floor can occur.

3.1.4 Target locations

The target locations are characterized by lumped-body locations dictated by acoustic and other considerations, the bathymetry of the bottom, water depth, condition of the benthic interface, and locations of other existing bodies. These characteristics will influence the amount of cable slack to be deposited between bodies, and the shape of the cable track lines between bodies on the bottom. The target locations will be of primary

importance in determining vessel speeds and headings and cable pay-out rates. Accuracy in achieving target locations is an objective function in the optimization of the installation process.

3.1.5 Environment

The environment consists of the wind, wave and current speed distributions (magnitudes and directions). In general, these distributions are random in nature and stochastic descriptions are necessary. However, deterministic descriptions of the environment will be useful in the development of the modeling methodologies. The environment influences the loading of the cables, lumped bodies and tow vessel. Since installation will proceed only during certain acceptable sea state conditions, extreme loadings need not be considered.

3.2 Mathematical Model

The dynamic behavior of the cable/lumped-body deployment system can be characterized by the evolution of its state variables, system parameters, controllable and uncontrollable inputs (see Figure 3.1).

3.2.1 State Variables

The state variables are: (1) locations of bodies (sonar packages) $S_i(t)$ during deployment operations, (2) position $(x(\ell, t), y(\ell, t), z(\ell, t))$ and tension $T(\ell, t)$ of the cable along its arc length ℓ , (3) fuel consumption $f(t, v_s)$, which is a function of deployment

time, and (4) total deployment time t_o , which is the time required to complete the deployment operation.

3.2.2 System Parameters

The specified parameters of the system are: (1) sonar target locations, St_i , (2) sonar dimensions, and (3) cable dimensions and material properties (size, shape, mass per unit length, etc.)

3.2.3 Controllable Inputs

The three major controllable inputs are: (1) vessel speed $v_s(t)$, (2) vessel heading which can be expressed as turning angle, $\theta_s(t)$, and (3) cable pay-out speed $v_c(t)$.

Other controllable variables may include: The initial position and velocity of the vessel, the time required to reach a constant speed (assuming a ramp function), the initial position of the cable/lumped-bodies, the time to start cable pay-out, and the spacing between lumped-bodies along the cable.

3.2.4 Uncontrollable Inputs

The uncontrollable inputs of the system considered are: (1) random wave surface profile $\eta(x,y,t)$, (2) spatial current speed $c(x,y,z,t)$, and (3) wind speed and direction. These uncontrollable inputs directly influence the hydrodynamic loading along the cable and on the lumped bodies.

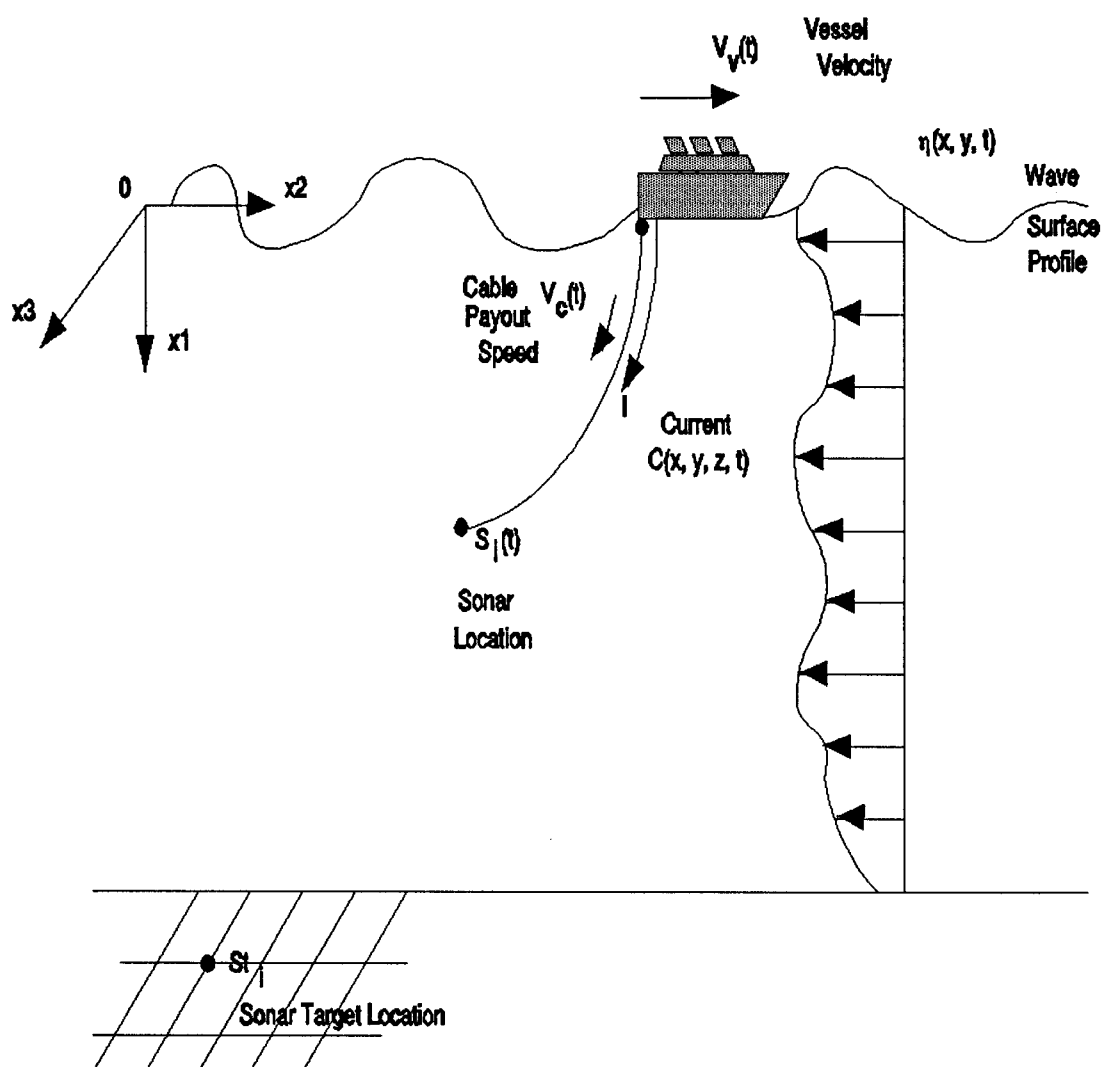


Figure 3.1 Definition Sketch of Cable/Lumped-Body Deployment System

3.3 Penalty Function

In a cable/lumped-body system, the penalty function expresses the "costs" of the cable deployment procedure as a function of the time history of the state variables. In a strict mathematical sense, it is a functional (that is, a function of a function or functions). Minimization of the penalty function ensures optimality of the deployment operation.

The penalty function can be specified in terms of the accuracy of placing the targets, the degree of difficulty of the deployment process, the time of deployment and the energy requirement. In this study, it is postulated to be directly proportional to: (1) the maximum tension in the cable winch during deployment operations; (2) the square of the tension in the cable at the winch, $T(0, t_j)$; (3) the square of the vessel velocity (power), $v_s(t_j)^2$; (4) the square of the cable pay-out speed (power), $v_c(t_j)^2$; (5) the change in vessel velocity, $[v_s(t_j) - v_s(t_{j-1})]$, at discrete times; (6) the change in cable pay-out speed, $[v_c(t_j) - v_c(t_{j-1})]$, at discrete times; (7) the inverse of the square of the radius of curvature of the cable, $r(0, t_j)^2$; (8) the distances (errors) between the targets and final actual sonar locations, $[S_i(t_o) - St_i]$, where $S_i(t_o)$ and St_i are the target locations and the actual sonar locations respectively; (9) the fuel consumption, $f(t_o)$; and (10) the total time of deployment, t_o .

A general mathematical description of the penalty function P is postulated as follows:

$$\begin{aligned}
P = & \gamma_1 T_{\max} + \sum_1^{t_o} \left[\gamma_2 T(0, t_j)^2 + \gamma_3 v_s(t_j)^2 + \gamma_4 v_c(t_j)^2 \right. \\
& + \gamma_5 | v_s(t_j) - v_s(t_{j-1}) | + \gamma_6 | v_c(t_j) - v_c(t_{j-1}) | \\
& \left. + \gamma_7 \frac{1}{r(0, t_j)^2} \right] + \sum_1^n \beta_i | S_i(t_o) - St_i | + \alpha_1 f(t_o) + \alpha_2 t_o
\end{aligned} \tag{1.a}$$

where $\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5, \gamma_6, \gamma_7, \beta_i, \alpha_1$, and α_2 are weighing parameters.

In this study, it is assumed that only one sonar will be deployed ($n = 1$), and that the effect of cable curvature can be neglected. Then, the penalty function can be simplified to the following:

$$\begin{aligned}
P = & \gamma_1 T_{\max} + \gamma_2 \sum_1^{t_o} T(0, t_j)^2 + \gamma_3 \sum_1^{t_o} v_s(t_j)^2 + \gamma_4 \sum_1^{t_o} v_c(t_j)^2 \\
& + \gamma_5 \sum_1^{t_o} | v_s(t_j) - v_s(t_{j-1}) | + \gamma_6 \sum_1^{t_o} | v_c(t_j) - v_c(t_{j-1}) | \\
& + \beta_1 | S_1(t_o) - St_1 | + \alpha_1 f(t_o) + \alpha_2 t_o
\end{aligned} \tag{1.b}$$

The values of the weight parameters can be chosen based on numerical simulation experience. The values of the tension at the winch, the vessel and pay-out speed were all nondimensionlized (with respect to the corresponding estimated maxima of the typical responses) prior to computing the penalty function. It is up to the users of the program to control the penalty caused by each variable by increasing or decreasing the value of its weighing parameter.

3.4 Operation Constraints

Typically a dynamic process is constrained to obey certain rules which may be equality constraints requiring the solution to lie in a definite path. The most important operational equality constraints that govern the deployment procedure of cable/lumped-body systems are the dynamic equilibria of the system at all times.

Inequality constraints prohibit some variables from exceeding certain limits during the installation procedure. For the cable deployment problem, two types of inequality constraints are encountered:

- (1) Operation constraints that are functions of the material properties of the cable/lumped-body system, and the capacity and maneuverability of the vessel. These constraints are: (a) specified minimum and maximum values of vessel speed, (b) specified minimum and maximum values of cable pay-out speed, (c) minimum vessel turning radius, (d) maximum cable curvature, and (e) minimum and maximum values of cable tension. Note that the minimum allowable tension must be positive.
- (2) Terminal operational state constraints which require the state variables to satisfy conditions at the end of the trajectory. For example, all lumped bodies must land within certain radii of target locations. One way to ensure the compliance of these constraints is to apply large weight parameter values on the final body locations.

3.5 Initial and Terminal Configurations

Initial and terminal conditions play an important role in the deployment operations of cable/lumped-body system. They can be classified as follows.

3.5.1 Initial Configurations

Two possible initial configurations are considered in this study (Figure 3.2):

- (I1) A static initial condition where a stationary vessel is positioned directly above the first lumped-body target, with the lumped body already lowered to the sea floor quasi-statically. This initial configuration is relatively easy to achieve with minimal uncertainty. Thus first target position can be achieved accurately under calm-sea condition. The initial equilibrium constraint on the cable/lumped-body system is static.
- (I2) A moving vessel, with initial constant velocity and no initial cable pay-out, heads towards the first target. Cable deployment begins when the vessel has reached a specified position. This initial configuration is also relatively easy to achieve without much uncertainty. However, the position of the first target may not be reached as accurately as in the first case.

3.5.2 Terminal Configurations

Similarly, two possible terminal configurations are considered:

- (T1) A static terminal condition where the vessel is stopped directly above the final target with zero cable pay-out speed and the final lumped body not yet touching

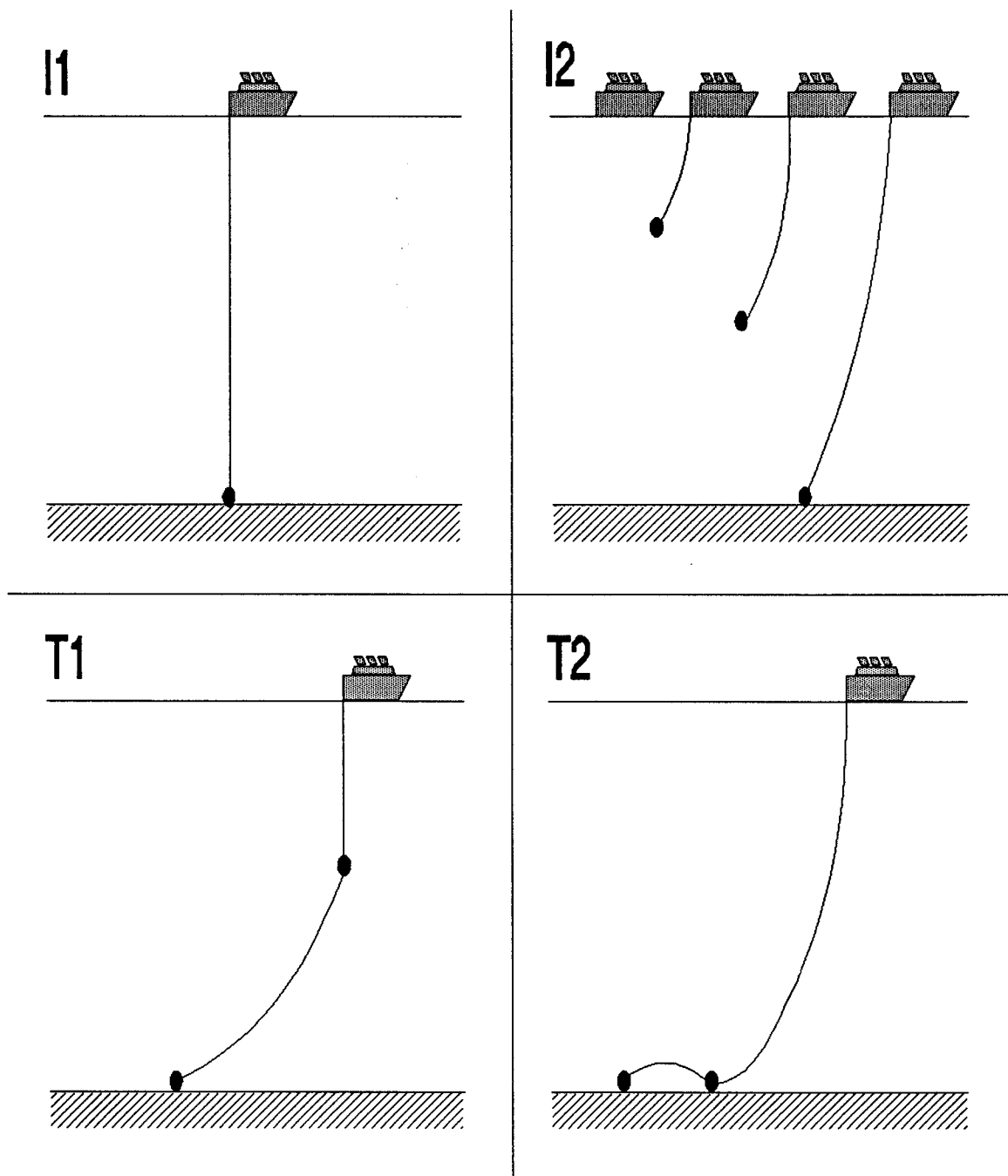


Figure 3.2 Initial (I1 and I2) and Terminal (T1 and T2) Configurations

the sea floor. Then lowering the final lumped body onto the sea floor quasi-statically. The final configuration is thus controlled by static constraints.

(T2) The (terminal) vessel and cable pay-out speeds are held constant through the deployment of the final target until it reaches the sea floor. Terminal configuration is defined as the configuration at the instant the final target contacts the sea floor.

3.6 Deployment Procedures

A deployment procedure can be characterized by its initial and terminal conditions, and its intermediate vessel velocities and cable pay-out speeds. Four possible deployment procedures considered in this study are:

- (D1) Static initial conditions (I1), constant vessel velocity (including possible turning) and cable pay-out speed between touchdown of individual targets, and static terminal conditions (T1).
- (D2) Static initial conditions (I1), constant vessel velocity (including possible turning) and cable pay-out speed between touchdown of individual targets, and dynamic terminal conditions (T2).
- (D3) Dynamic initial conditions (I2), constant vessel velocity (including possible turning) and cable pay-out speed between touchdown of individual targets, and static terminal conditions (T1).
- (D4) Dynamic initial conditions (I2), constant vessel velocity (including possible

turning) and cable pay-out speed between touchdown of individual sonar packages, and dynamic terminal conditions (T2).

3.7 Deployment segmentation

The above deployment procedures can be constructed by assembling a selected sequence of the following deployment segments (Figure 3.3):

- (S1) Deployment of the first target, with zero initial cable length, constant cable pay-out speed and constant vessel acceleration until a specified constant speed is reached. This segment handles the (I2) initial configuration.
- (S2) Deployment of the i^{th} target at constant vessel velocity and cable pay-out speed, with $i-1^{\text{st}}$ target anchored at the sea floor, and no consideration of the presence of the $i+1^{\text{st}}$ target. This segment handles intermediate deployment steps, static initial configuration (S1), and dynamic terminal configuration (T2).
- (S3) Deployment of the i^{th} and the $i+1^{\text{st}}$ targets in sequence, each at (possibly different) constant vessel velocity and cable pay-out speed, with the $i-1^{\text{st}}$ target anchored at the sea floor. The $i+1^{\text{st}}$ target is introduced during the deployment of the i^{th} one, thus influencing the optimal deployment path of the i^{th} target. This segment handles intermediate deployment steps with two sonar packages being deployed simultaneously.
- (S4) Deployment of the $n-1^{\text{st}}$ and the n^{th} target in sequence, with the $n-2^{\text{nd}}$ target anchored at the sea floor. The $n-1^{\text{st}}$ target is deployed at constant vessel velocity and cable pay-out speed, the n^{th} (last) sonar is deployed statically with vessel

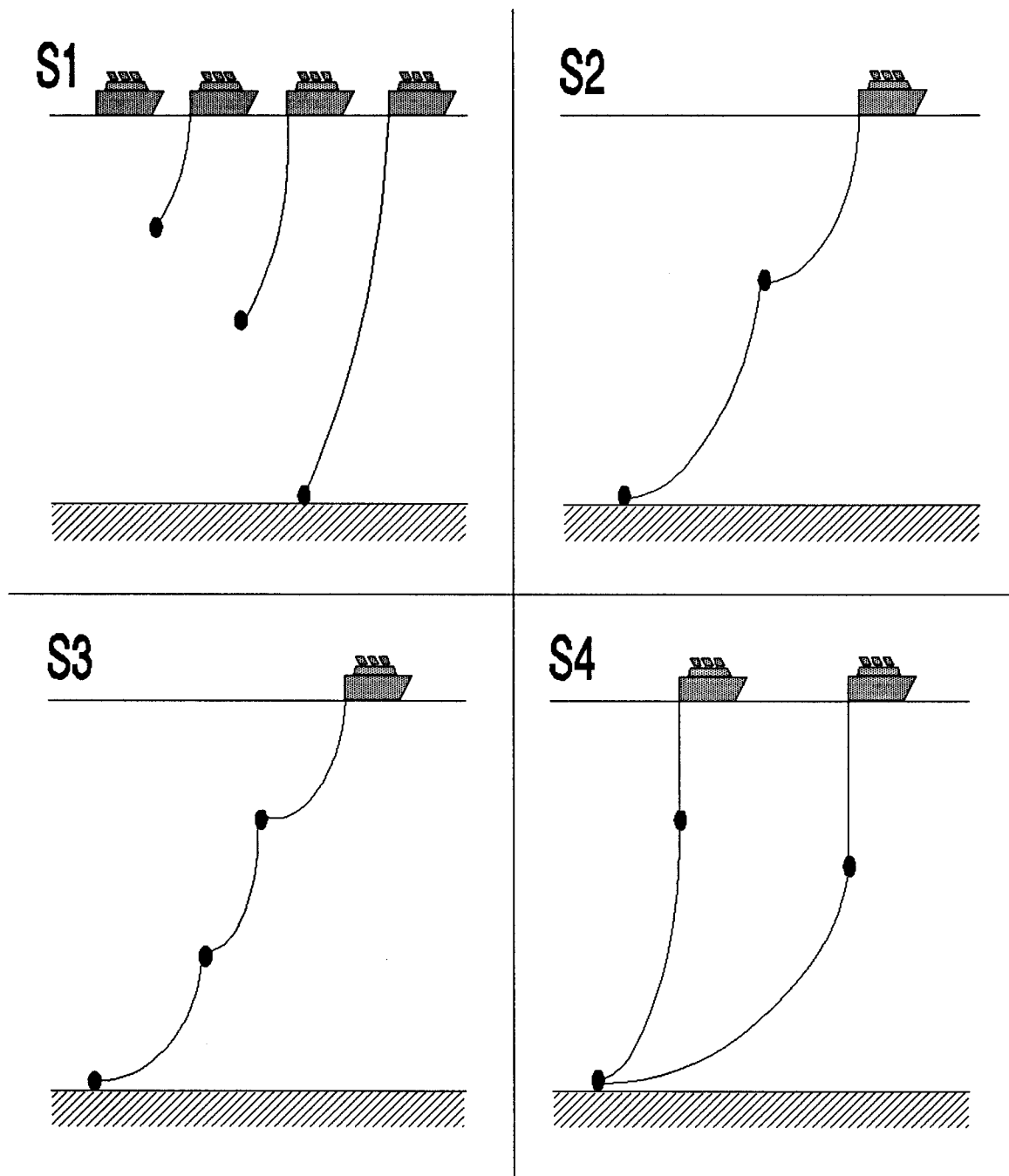


Figure 3.3 Cable/Lumped-Body Deployment Procedure Segments

directly positioned above final sonar target. This segment handles the static terminal configuration (T1).

It is assumed that optimization of the deployment procedure can be achieved by optimizing the individual segments (S1-S4). Optimization of segments (S1) and (S2) can be developed independently. Optimization of segment (S3) can be achieved iteratively with the presence of the second lumped body considered a perturbation to the single lumped-body optimal procedure in segment (S2). By the same token, the optimization procedure can be extended to the deployment of three or more lumped bodies.

In this study, using a preliminary version of the KBLDYN program which included some limitations on solving deployment scenarios, segments S1, S2, and S3 can be examined. However in each of these segments, only one body can be optimized. When a modified KBLDYN program which deals with deployment of more than one body becomes available, the optimization will be extended to two or more bodies.

3.8 Optimization Algorithms

In order to find the minimum value of the penalty function P by a general search algorithm, it is necessary for P to satisfy some smoothness conditions. Because it is costly to search through the entire space of the variables, most algorithms economize on the number of function evaluations by first evaluating the penalty function P over a prescribed grid, and then searching for the minimum near the point corresponding to the lowest calculated value of the penalty function (Figure 3.4). It is possible that, depending on the grid size and the initial position, the search may converge to a local

minimum instead of a global one. This can be demonstrated clearly for a two-dimensional case in Figure 3.5, where $z = P$ describes a surface in three dimensions, and the optimal point is the one on the surface that is furthest below the plane $z = 0$. This deficiency seems to be inevitable in general optimization methods. To improve on the probability of converging to the global minimum, different (successively finer) grid sizes be tried if it is suspected that P might contain several local minima.

Each of the four segments mentioned in the previous section can be optimized by varying the three controllable parameters, vessel speed, vessel heading, and cable pay-out speed. Since within each segment the parameters are assumed to be constant, the optimal point can be located using an alternating direction method introduced in the following section.

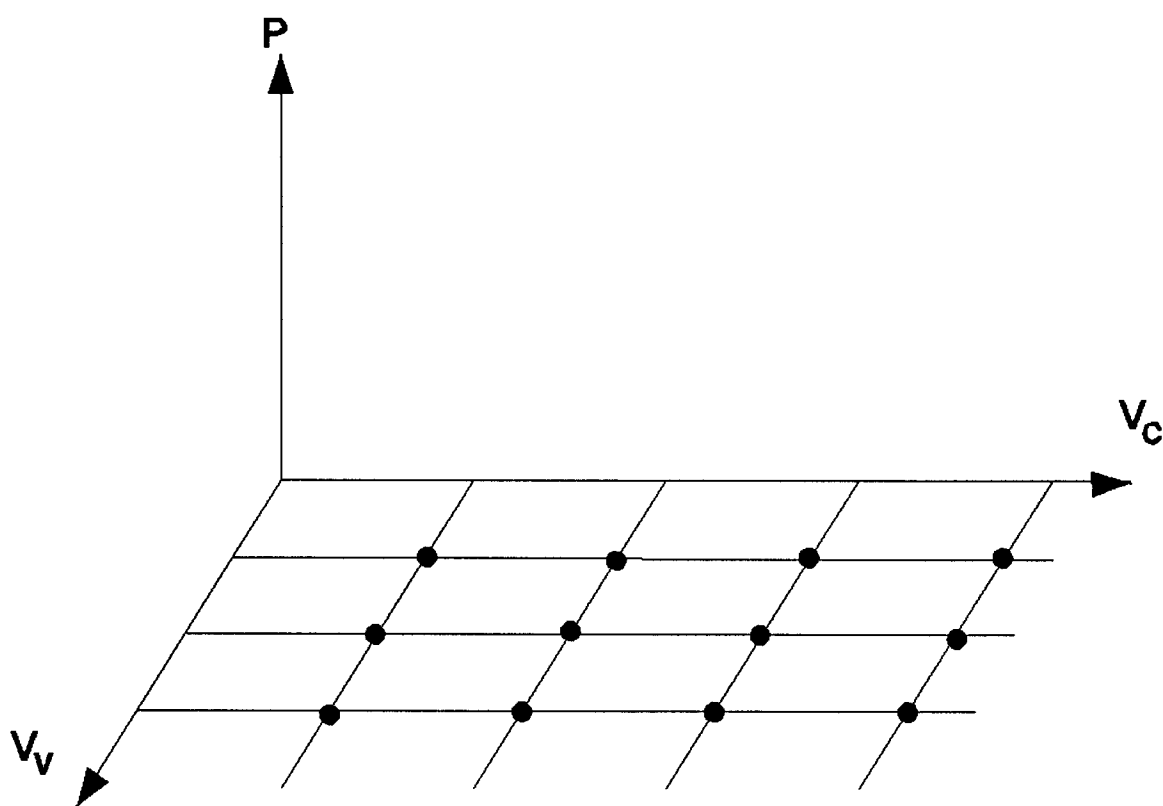


Figure 3.4 Initial Search Grid for Optimization Procedure

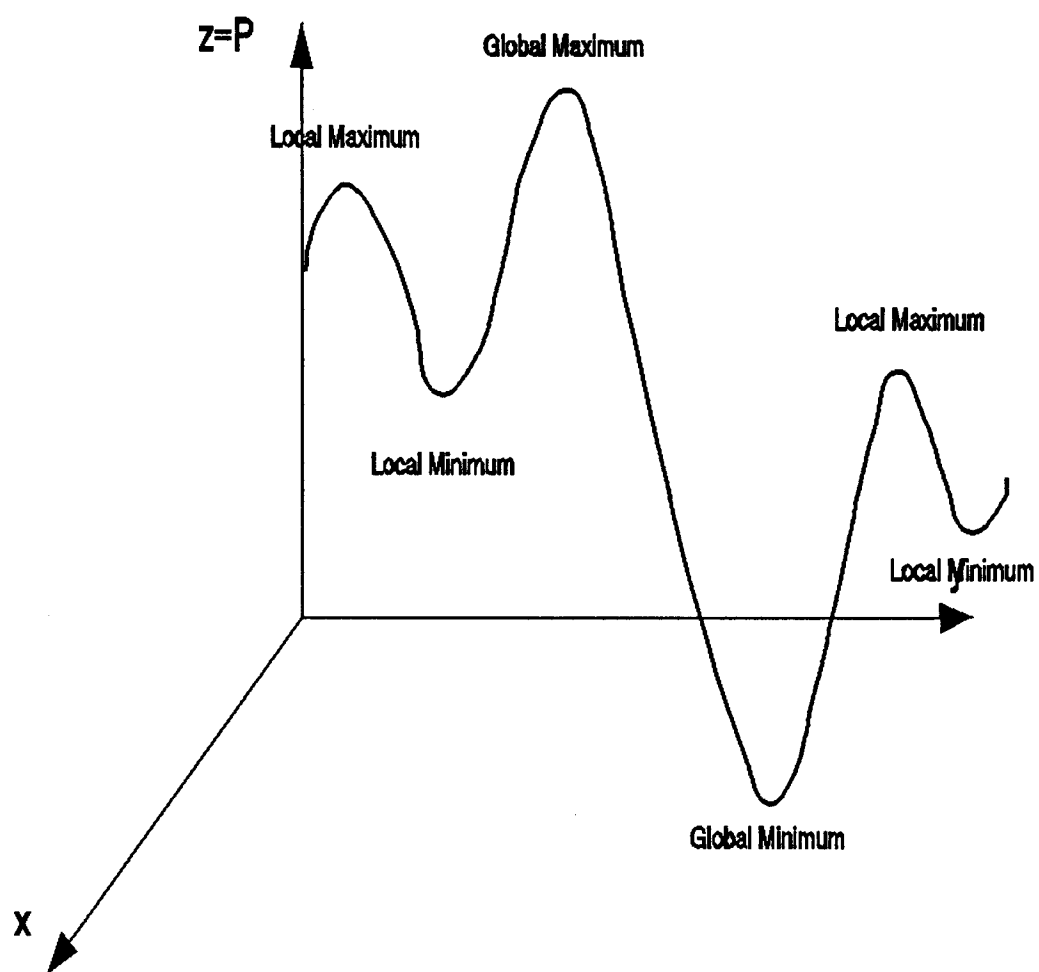


Figure 3.5 General Definition of Local Minimum and Local Maximum

3.8.1 Two-Dimensional Case

If the deployment is along a straight line (no vessel turning), the optimization search is in a two-dimensional space, with only the vessel speed and the cable pay-out speed being considered.

Algorithm 1: Alternating Direction Method (ADM)

This method relies on evaluating the penalty function P at a sequence of points along alternating axes and comparing the values of P at the adjacent points in order to reach the optimum value (Figure 3.6).

- Step 1. Initialize the search procedure by using the vessel speed $v_s(i)$ and the cable pay-out speed $v_c(i)$ corresponding to the minimum penalty function found from the grid search as initial values.
- Step 2. Use the KBLDYN program to determine the location of the cable and sonar package for time $t > 0$. Integrate until the sonar touches the sea floor. Evaluate the penalty function P as a function of the total time t_o , vessel speed v_s , cable pay-out speed v_c , sonar-target distance, and the other state variables.
- Step 3. Increase the vessel speed to $v_s(i+1) = v_s(i) + dv_s$, and repeat step 2. If the new P is lower than the old P , then replace the vessel speed $v_s(i)$ by $v_s(i+1)$. Otherwise decrease the vessel speed to $v_s(i+1) = v_s(i) - dv_s$, and repeat step 2. If the new P is lower than the old P , then replace vessel speed $v_s(i)$ with $v_s(i+1)$. If neither the increased nor the decreased vessel

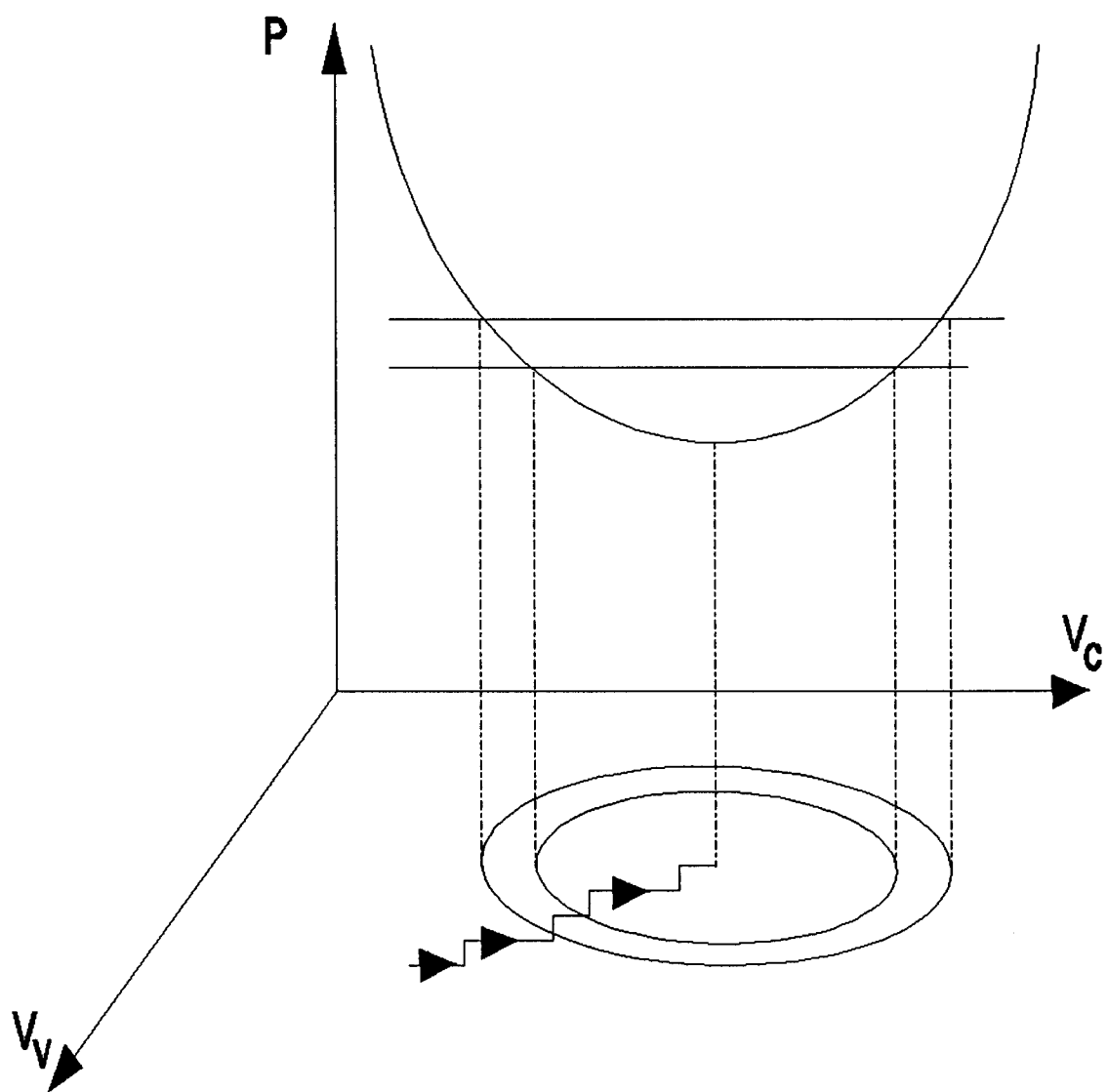


Figure 3.6 Alternating Direction Method for Optimization

speed values give a lower new penalty P , then $v_s(i)$ is used on the next step.

Step 4. Increase the cable pay-out speed to $v_c(i+1) = v_c(i) + dv_c$, and repeat step 2. If the new P is lower than the old P , then replace the cable pay-out speed $v_c(i)$ with $v_c(i+1)$. Otherwise decrease the cable pay-out speed to $v_c(i+1) = v_c(i) - dv_c$, and repeat step 2. If the new P is lower than the old P , then replace the cable pay-out speed $v_c(i)$ with $v_c(i+1)$. If neither the increased nor the decreased cable pay-out speed values give a lower new penalty value, then $v_c(i)$ is used on the next step.

Step 5. Repeat step 3 and 4 until the penalty function P reaches a local minimum, which happens when P can not be decreased by repeating step 3 and 4. This local minimum corresponds to the one closest to the minimum penalty function grid point. Thus is also likely to be the global minimum.

The constraint conditions, i.e., the minimum and maximum values of the vessel speed, and the minimum and maximum values of the cable pay-out speed, are enforced throughout this algorithm. In addition, the cable pay-out speed is kept at 1.25 times or greater than the vessel speed, throughout the algorithm to ensure that the body will descend onto the sea floor.

Algorithm 2: Modified Alternating Direction Method

The Modified Alternating Direction Method (MADM) differs from ADM in that it searches for the minimum along each axis and does not change direction until a

minimum on that axis has been reached (Figure 3.7). In other words, one variable will be either increased or decreased over and over until a minimum value of the penalty function has been reached. At this point it switches to the other variable and searches for a local minimum along that axis. The procedure will repeat itself until a minimum value of the penalty function corresponding to both axes is found.

- Step 1. Initialize the search procedure by using the vessel speed $v_s(i)$ and the cable pay-out speed $v_c(i)$ corresponding to the minimum penalty function found from the grid search as the initial values.
- Step 2. Use the KBLDYN program to determine the location of the cable and the sonar package for time $t > 0$. Integrate until the sonar touches the sea floor. Evaluate the penalty function P as a function of the total time t_o , vessel speed v_s , cable pay-out speed v_c , sonar-target distance, and other state variables.
- Step 3. Increase the vessel speed to $v_s(i+1) = v_s(i) + dv_s$, and repeat step 2. If the new P is lower than the old P , then replace the vessel speed $v_s(i)$ with $v_s(i+1)$. Otherwise decrease the vessel speed to $v_s(i+1) = v_s(i) - dv_s$, and repeat step 2. If the new P is lower than the old P , then replace the vessel speed $v_s(i)$ with $v_s(i+1)$. Repeat this step until a greater penalty function occurs in both directions (increasing and decreasing). Then replace $v_s(i)$ with $v_s(i+n)$ (the last vessel speed value that results in a lower penalty function).

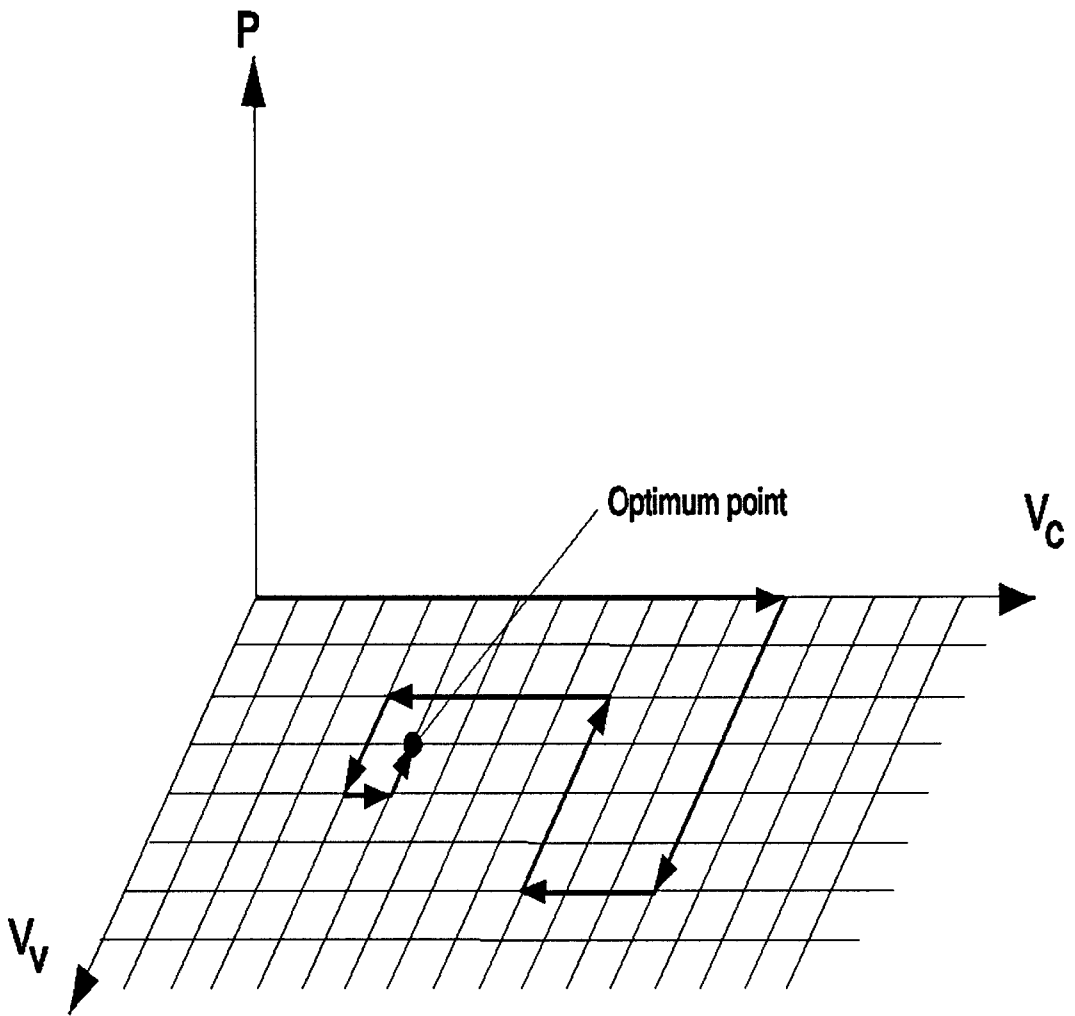


Figure 3.7 Modified Alternating Direction Method for Optimization

- Step 4.** Increase the cable pay-out speed to $v_c(i+1) = v_c(i) + dv_c$, and repeat step 2. If the new P is lower than the old P , then replace the cable pay-out speed $v_c(i)$ with $v_c(i+1)$. Otherwise decrease the cable pay-out speed to $v_c(i+1) = v_c(i) - dv_c$, and repeat step 2. If the new P is lower than the old P , then replace cable pay-out speed $v_c(i)$ with $v_c(i+1)$. Repeat this step until a greater penalty function occurs in both directions (increasing and decreasing). Then replace $v_c(i)$ with $v_c(i+m)$ (the last pay-out value that results in a lower penalty function.)
- Step 5.** Repeat step 3 and 4 until P reaches a local minimum. This occurs when both in step 3 and 4, the penalty function does not get any lower. For smooth penalty P , this local minimum corresponds to the one closest to the minimum penalty function grid point. This is also likely to be the global minimum.

3.8.2 Three-Dimensional Case

The three-dimensional case is similar to the two-dimensional case above, except that one more variable (vessel turning velocity) will be introduced, and the search is in a three-dimensional space.

CHAPTER 4 NUMERICAL EXAMPLES

In this chapter three major examples to demonstrate the capability of the optimization algorithms developed above are presented. Both algorithms have been used in optimizing the cable deployment procedures. However, because they yield identical results in all case tests, only the first algorithm is discussed in depth.

The first example explores the deployment of one body with finite initial cable length. Two cases are selected, one with a very short length, another with an intermediate length. The very short length is selected because it reflects the deployment of the first sonar package in the operations. The second case considers the deployment of an initially submerged body hanging directly below the vessel at a specified finite depth. Example 2 examines the deployment of one lumped body with the cable initially touching the sea floor. Example 3 examines the optimization of the deployment of two bodies in sequence, also with the cable initially touching the sea floor. Due to the limitations of the earlier version of the KBLDYN program, optimization is only executed on the first body.

4.1 Example 1(a): Object/Zero Initial Cable Length

Figure 4.1 demonstrates the deployment of the first sonar package with zero initial vessel speed and a very short cable length ($L = 0.8$ m). For time $t > 0$, the cable pay-out speed is constant and the vessel undergoes a constant acceleration until it

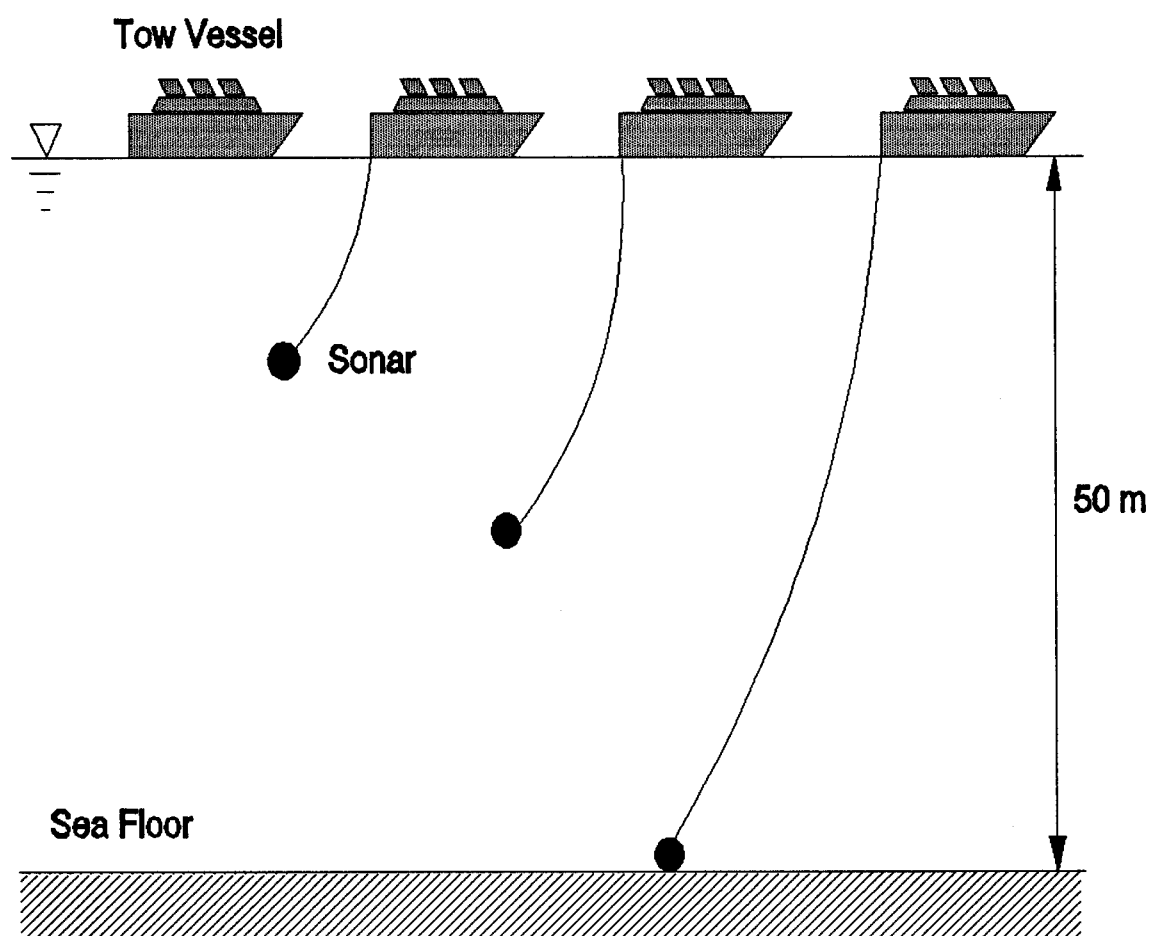


Figure 4.1 Deployment of Lumped-Body with Zero Initial Cable Length

reaches a specified speed. The major input data are summarized in Table 4.1. These values are selected based on numerical simulation experience and information supplied by the Naval Civil Engineering Laboratory.

Vessel Speed Ramp Function Duration	= 40 sec
Cable Length	= 0.8 m
Time Step Size	= 2 sec
Water Depth	= 50 m
Minimum Vessel Speed	= 0.1 m/sec
Maximum Vessel Speed	= 1.0 m/sec
Vessel Speed Grid Division	= 0.2 m/sec
Vessel Speed Search Division	= 0.01 m/sec
Minimum Cable Pay-Out Speed	= 0.2 m/sec
Maximum Cable Pay-Out Speed	= 2.0 m/sec
Cable Pay-Out Speed Grid Division	= 0.4 m/sec
Cable Pay-Out Speed Search Division	= 0.2 m/sec
Target Distance from Starting Point	= 10.0 m

Table 4.1 Input Data for Example 1(a).

The values of the weight parameters for this example are listed in Table 4.2, where γ_1 consists of the value that effect the penalty caused by the maximum tension, γ_2 consists of the value that effects the penalty caused by the tension during the deployment

operation, etc.. (eq 1.b)

$\gamma_1 = 2.0$	$\gamma_2 = 1/15$	$\gamma_3 = 1.0$
$\gamma_4 = 0.2$	$\gamma_5 = 2.0$	$\gamma_6 = 1.0$
$\beta_1 = 3.0$	$\alpha_1 = 1.0$	$\alpha_2 = 1.0$

Table 4.2 Weight Parameter Values for Example 1(a).

The optimal initial search point found from the grid search is ($v_s = 0.30$, $v_c = 0.6$) with the corresponding penalty function value $P = 11.514$. After performing the ADM optimization procedure, starting from the optimum grid point, the global minimum point is found to be ($v_s = 0.27$, $v_c = 0.6$) with a penalty function value of $P = 8.930$. This (global minimum) value is confirmed by searching through the entire (2-D) space using very fine divisions.

The users of the program are cautioned that if larger values of grid divisions for the initial grid search are used, the optimization algorithm may lead to a local minimum instead of the global minimum. This phenomenon can be demonstrated by the following example with grid divisions:

Cable pay-out division = 0.4 m/sec

Vessel speed division = 0.3 m/sec

Using these values, the grid search lead to an optimal search point of ($v_s = 0.70$, $v_c = 1.4$) with penalty function value $P = 11.867$. Then the optimization procedure lead to a local minimum point ($v_s = 0.70$, $v_c = 1.2$) with penalty function value $P = 11.055$,

which is different from the global minimum found above. This behavior can be explained as follow. For large grid search divisions (for both vessel speed and cable pay-out speed) the area near the global minimum may be missed during the grid search. The topographic plot of this example, Figure 4.2, shows that the global minimum is located in a steep valley that is very easily bypassed if big grid divisions are used. To ensure the success of the search procedure, a smaller grid division has to be used. However, since a decrease in grid division leads to larger computation time, an "optimum" grid division should be properly chosen.

The global minimum point is shown in Figure 4.3. One can imagine how other local minima could be wrongly selected as global minimum should the adopted grid size not have been sufficiently fine. Note that the two high hills (large penalty values) are results of the large weight parameters put on the distance error between the target and the final actual sonar location.

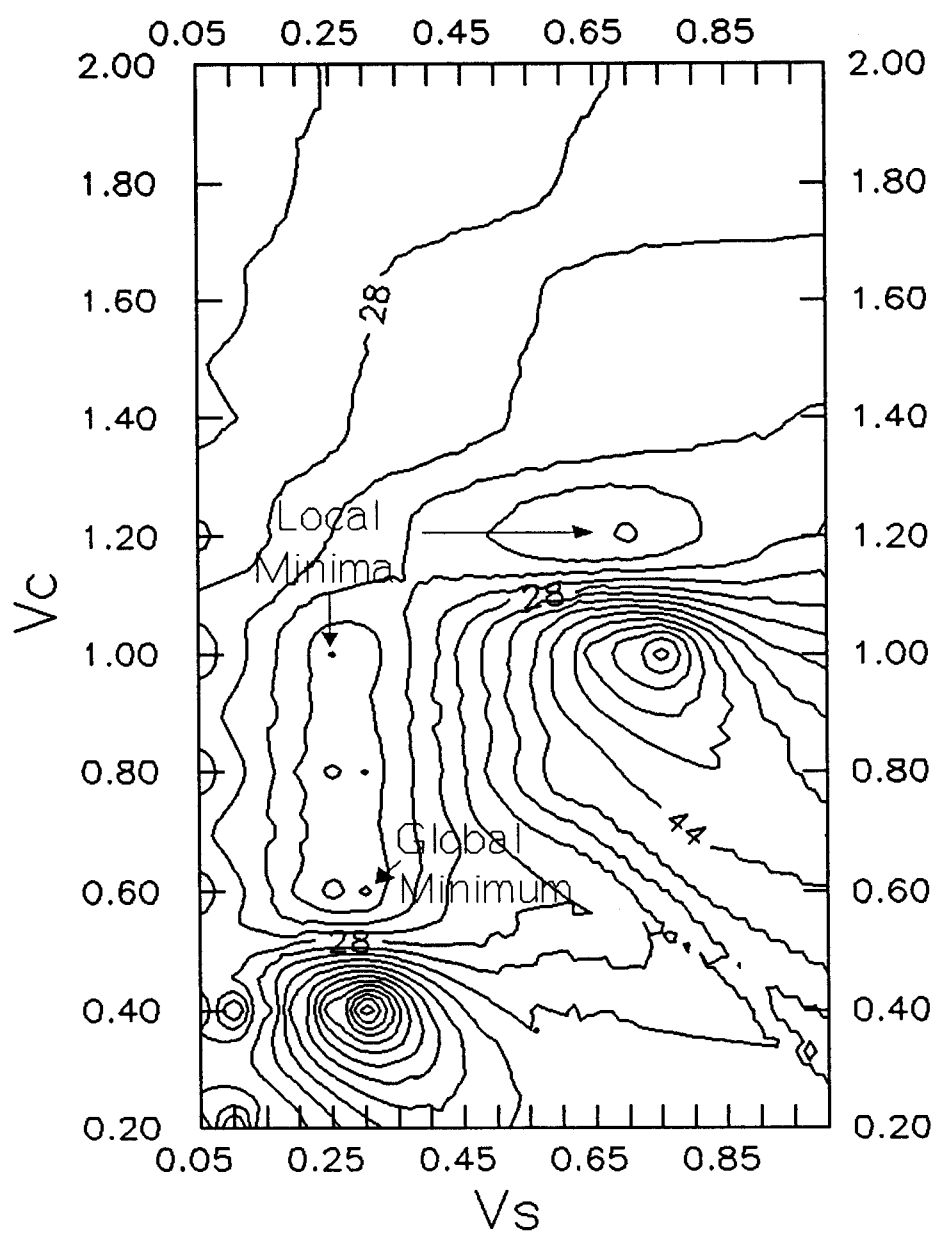


Figure 4.2 Topographic Plot of Penalty Function, Example 1(a)

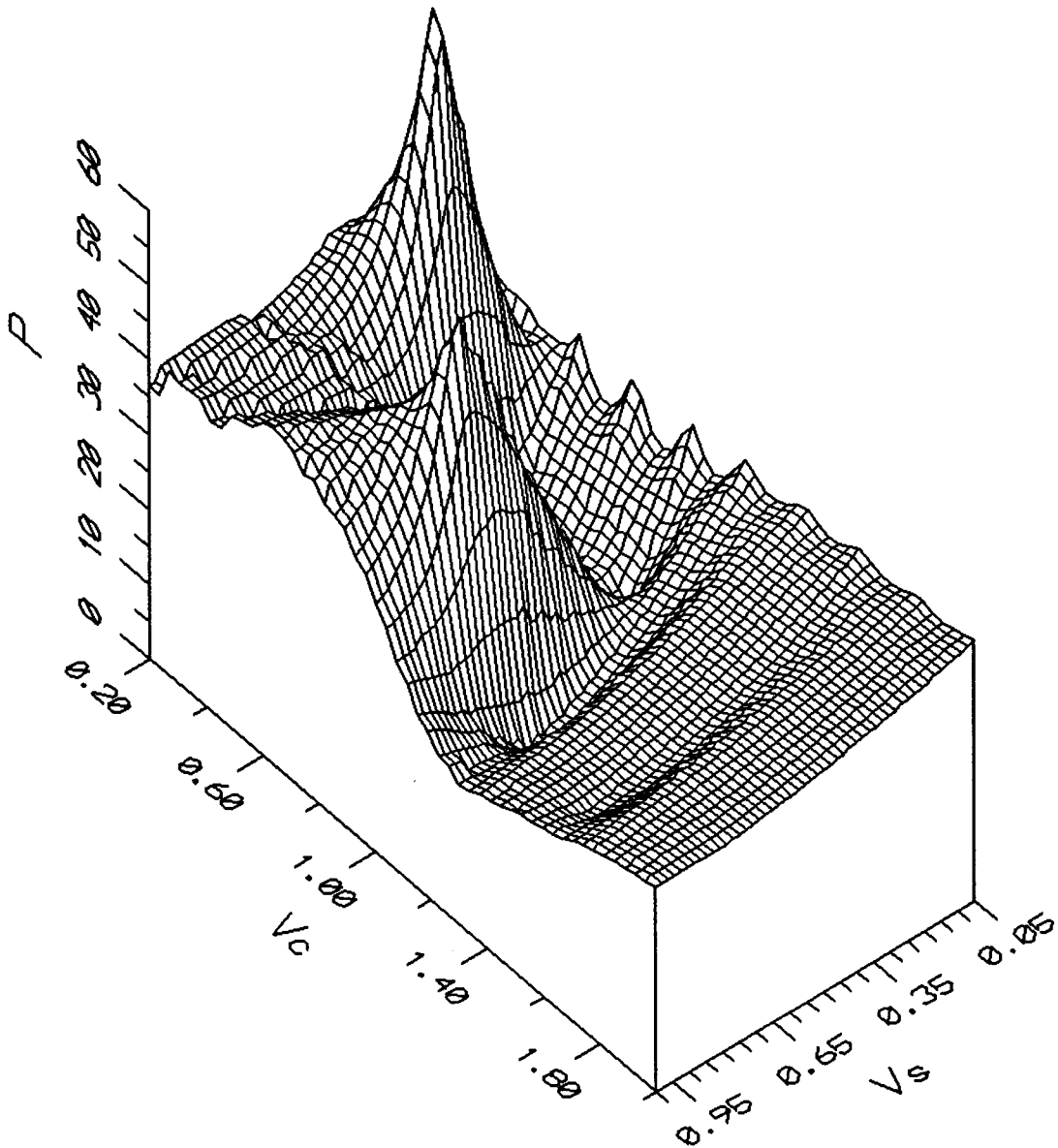


Figure 4.3 Penalty Function vs Vessel and Cable Pay-Out Speeds, Example 1(a)

4.2 Example 1(b): Towed Cable/Object

This example is similar to Example 1(a) but with a longer initial cable length (see Figure 4.4). At time $t = 0$, the tow vessel is in a standstill condition with a sonar package hanging directly below the vessel. For time $t > 0$, the cable pay-out speed is constant and the vessel moves at a constant acceleration until it reaches a specific vessel speed. The input data are the same as the previous example except for the initial cable length ($L = 20$ m), the water depth ($D = 60$ m), and the target distance from the starting point ($St_1 = 5$ m) (see Table 4.3). The weight parameters used in this example are listed in Table 4.4. Different values were examined to test robustness of the program.

The optimum initial search point found from the grid search is ($v_s = 0.20$, $v_c = 0.8$). Using this point to start the ADM search procedure, the final global point is found to be ($v_s = 0.19$, $v_c = 0.8$).

The grid division used in this example is acceptable since it leads to the correct area where the global point exists. This result is also confirmed through a very fine grid evaluations as in the previous example.

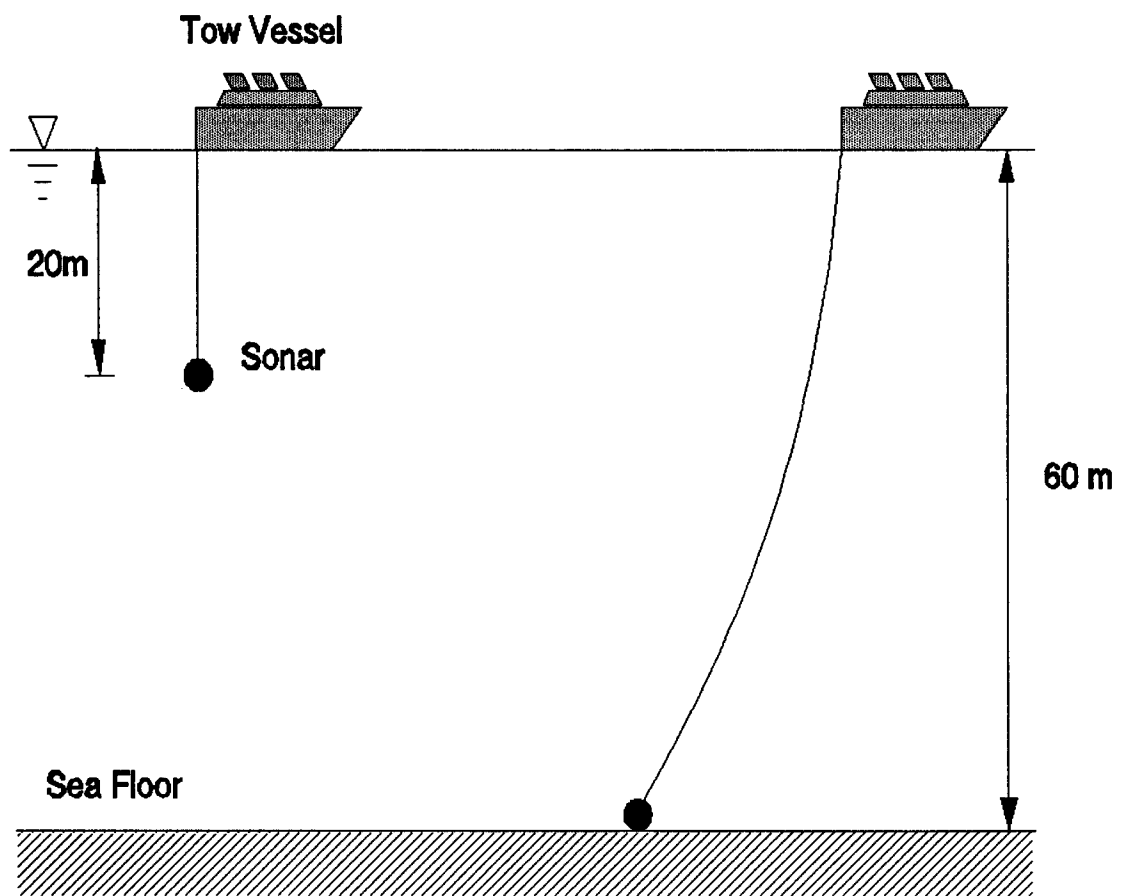


Figure 4.4 Definition Sketch of Towed Cable/Lumped-Body System

Vessel Speed Ramp Function Duration	= 40 sec
Cable Length	= 20.0 m
Time Step Size	= 2 sec
Water Depth	= 60 m
Minimum Vessel Speed	= 0.1 m/sec
Maximum Vessel Speed	= 1.0 m/sec
Vessel Speed Grid Division	= 0.1 m/sec
Vessel speed Search division	= 0.01 m/sec
Minimum Cable Pay-Put Speed	= 0.2 m/sec
Maximum Cable Pay-Out Speed	= 2.0 m/sec
Cable Pay-Out Speed Grid Division	= 0.6 m/sec
Cable Pay-Out Speed Search Division	= 0.2 m/sec
Target distance from Starting Point	= 5.0 m

Table 4.3 Input Data for Example 1(b).

$\gamma_1 = 2$	$\gamma_2 = 1/15$	$\gamma_3 = 1$
$\gamma_4 = 2$	$\gamma_5 = 4$	$\gamma_6 = 1$
$\beta_1 = 3$	$\alpha_1 = 1$	$\alpha_2 = 1$

Table 4.4 Weight Parameter Values for Example 1(b).

4.3 Example 2: Cable/Lumped-Body/Cable

This example illustrates the deployment of a lumped-body with the cable initially touching the sea floor. As displayed in Figure 4.5, it is composed of two cable segments and an intermediate body. The pay-out operation is started at time $t = 0$ with a specified constant pay-out rate and the vessel undergoes a constant acceleration until it reaches a specified constant speed. The input data are summarized in Table 4.5. The weight parameter values used in this example are listed in Table 4.6 and are the same as used in Example 1a.

Vessel Speed Ramp Function Duration	= 40 sec
Time Step Size	= 2.5 sec
Water Depth	= 51.0 m
Minimum Vessel Speed	= 0.1 m/sec
Maximum Vessel Speed	= 0.5 m/sec
Vessel Speed Grid Division	= 0.1 m/sec
Vessel Speed Search Division	= 0.01 m/sec
Minimum Cable Pay-Out Speed	= 0.2 m/sec
Maximum Cable Pay-Out Speed	= 1.0 m/sec
Cable Pay-out Speed Grid Division	= 0.4 m/sec
Cable Pay-out Speed Search Division	= 0.2 m/sec
Target Distance from Starting Point	= 5.0 m

Table 4.5 Input Data for Example 2.

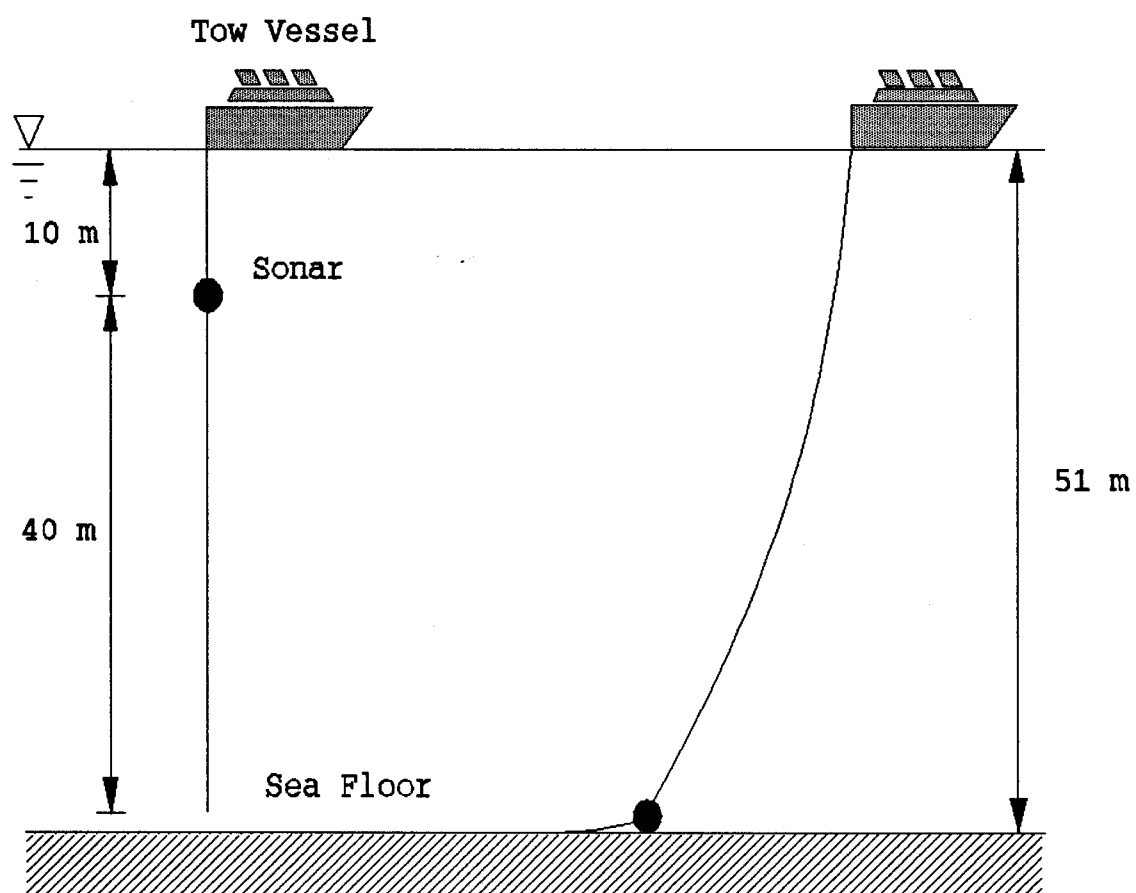


Figure 4.5 Definition Sketch of Cable/Lumped-Body/Cable System

$\gamma_1 = 2.0$	$\gamma_2 = 1/15$	$\gamma_3 = 1.0$
$\gamma_4 = 0.2$	$\gamma_5 = 2.0$	$\gamma_6 = 1.0$
$\beta_1 = 3.0$	$\alpha_1 = 1.0$	$\alpha_2 = 1.0$

Table 4.6 Weight Parameter Values for Example 2.

The grid search leads to a optimal initial search point of ($v_s = 0.10$, $v_c = 0.40$). Starting from this point and performing the optimization procedure, the global minimum point is found to be ($v_s = 0.11$, $v_c = 0.40$). This result is confirmed using the second algorithm and the entire search grid.

4.4 Example 3: Cable/Lumped-Bodies/Cable

This example illustrates the deployment of two sonar packages in sequence, although optimization is performed only for the deployment of the first sonar. As depicted in Figure 4.6, the system is composed of three cable segments and two intermediate bodies. The pay-out operation is started at time $t = 0$ with a specified constant pay-out rate and the vessel moves with a constant acceleration until it reaches a specified constant speed. The input data and the weight parameters used are summarized in Tables 4.7 and 4.8, respectively. These values are different than those used in previous examples to test the robustness of the optimization procedure.

As seen in the previous examples, the search for the global minimum was conducted by first evaluating the penalty function for various combinations of the vessel

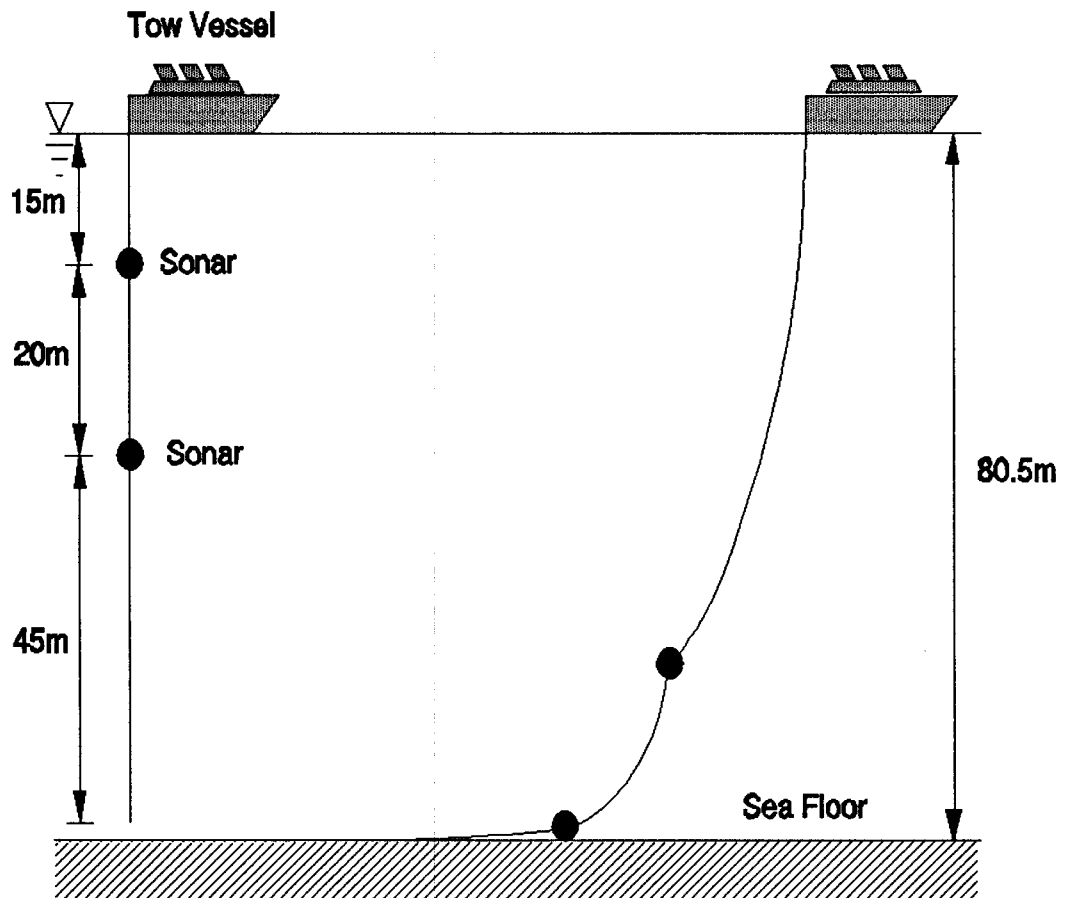


Figure 4.6 Definition Sketch of Cable/Lumped-Bodies/Cable System

speed and pay-out speed values on a coarse grid. An optimal initial search point is found to be ($v_s = 0.30$, $v_c = 0.6$). Using the ADM procedure, the global minimum point is found to be ($v_s = 0.27$, $v_c = 0.6$) (Figure 4.7). As before, this point is confirmed using the MADM procedure and a very fine grid evaluation (see Figure 4.8).

Vessel Speed Ramp Function Duration	= 40 sec
Time Step Size	= 2.5 sec
Water Depth	= 80.5 m
Minimum Vessel Speed	= 0.1 m/sec
Maximum Vessel Speed	= 0.7 m/sec
Vessel Speed Grid Division	= 0.1 m/sec
Vessel Speed Search Division	= 0.01 m/sec
Minimum Cable Pay-Out Speed	= 0.2 m/sec
Maximum Cable Pay-Out Speed	= 1.0 m/sec
Cable Pay-Out Speed Grid Division	= 0.4 m/sec
Cable Pay-Out Speed Search Division	= 0.2 m/sec
Target Distance from Starting Point	= 5.0 m

Table 4.7 Input Data for Example 3.

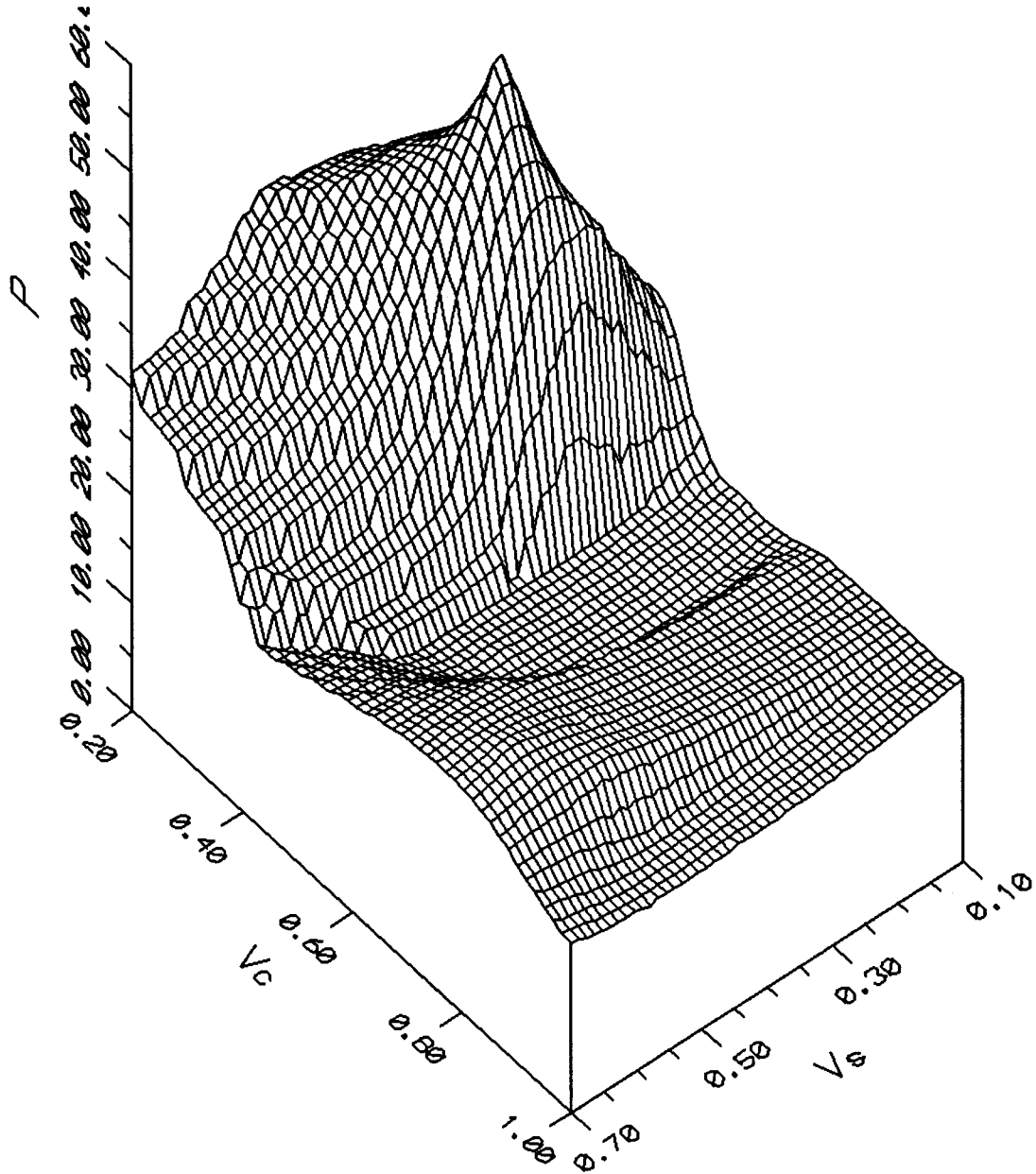


Figure 4.7 Penalty Function vs Vessel and Cable Pay-Out Speeds, Example 3

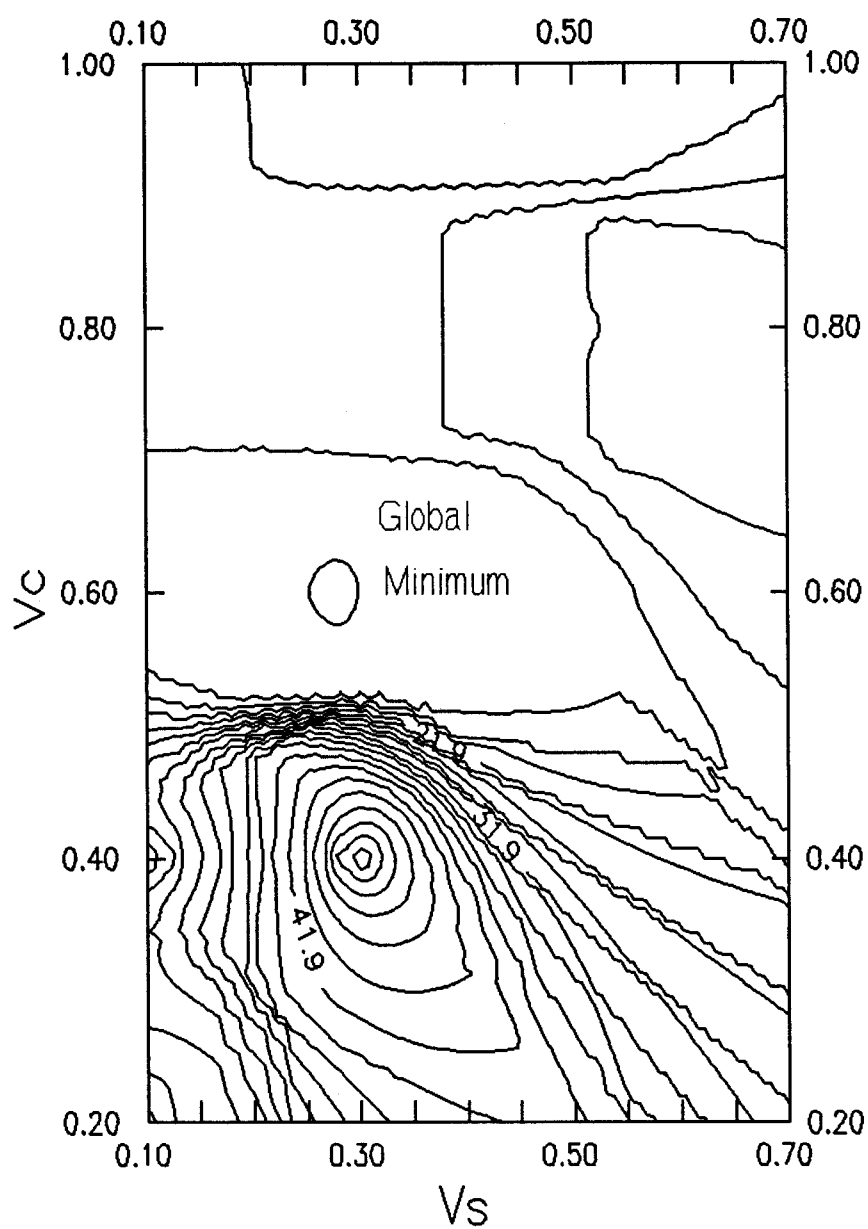


Figure 4.8 Topographic Plot of Penalty Function, Example 3

$\gamma_1 = 2.0$	$\gamma_2 = 1/15$	$\gamma_3 = 1.0$
$\gamma_4 = 0.2$	$\gamma_5 = 4.0$	$\gamma_6 = 1.0$
$\gamma_7 = 3.0$	$\gamma_8 = 1.0$	$\gamma_9 = 1.0$

Table 4.8 Weight Parameter Values for Example 3.

CHAPTER 5 CONTROL OF CABLE/LUMPED-BODY DEPLOYMENT SYSTEMS

5.1 Role of Control Systems

The term control refers to the process of deliberately influencing the behavior of an object so as to produce some desired results. The physical device inserted for this purpose is the controller. The role of the controller is twofold: (1) it must bring the system's operating condition to the desired value, and (2) it must maintain the desired condition in the presence of variations caused by the external environment. In other words, the controller must respond satisfactorily to changes in commands and maintain system performance in the presence of disturbances. In general one or more controllers are often required in complex dynamic systems in order to make the system elements act together to achieve the intended goal (Palm, 1983).

5.2 Formulation of Control Systems

A control system is a dynamic system that behaves in a prescribed manner without human interference. The analysis of control systems relies upon system theory where the governing differential equations are of the type of a cause-effect relationship (Doebelin, 1985; Anand, 1984). A general physical system is depicted in Figure 5.1. A representation of the corresponding control system is shown in Figure 5.2 with the following essential components: (1) the plant, which is the system to be controlled, (2) measuring devices (sensors), which give information about the plant, and (3) the

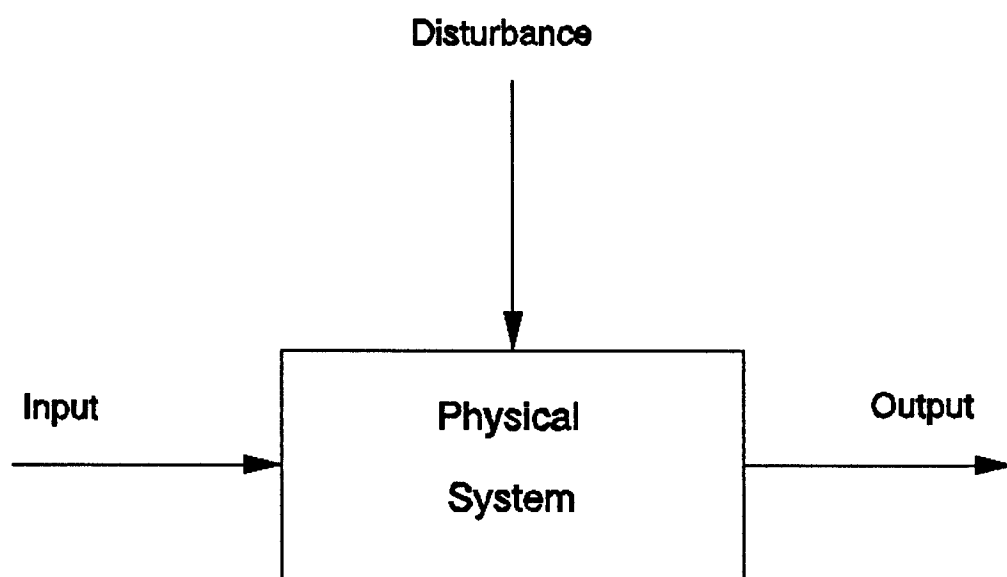


Figure 5.1 General Physical System

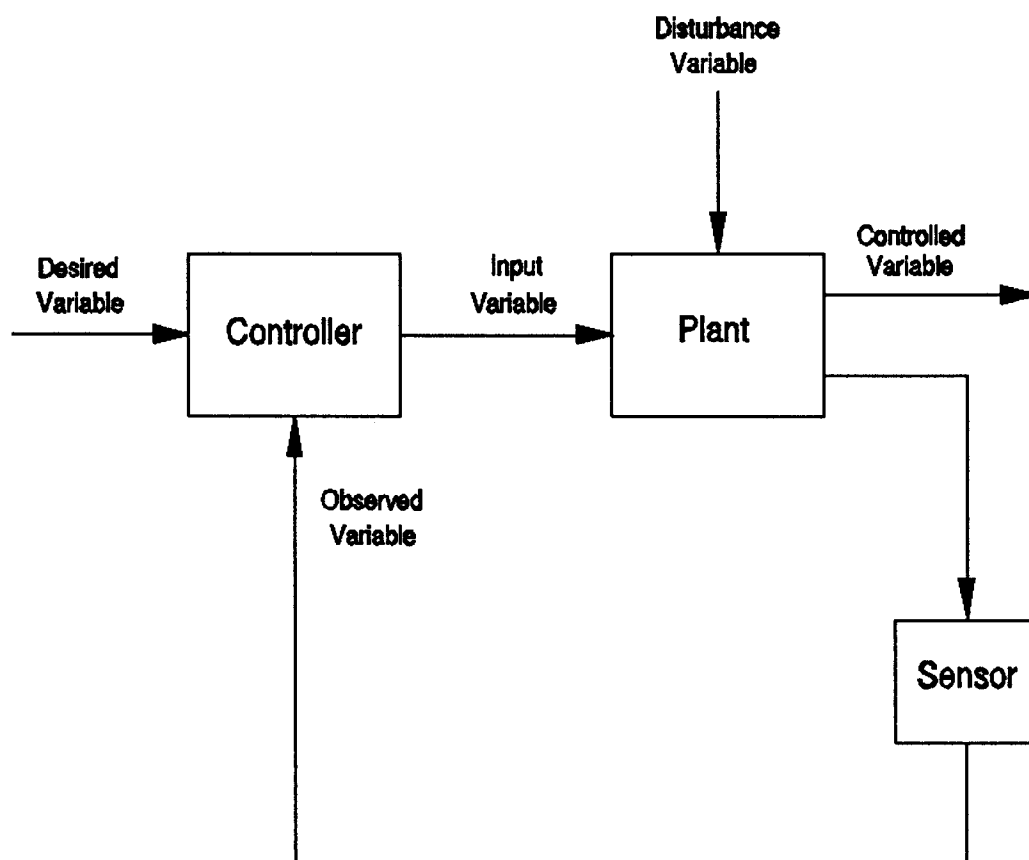


Figure 5.2 General Control System with Closed Loop

controller, which compares the measured values to their desired values and adjusts the input variables to the plant. A typical control system usually contains the following groups of variables: (1) input variables which influence the plant and which can be manipulated; (2) disturbance variables which influence the plant but which can not be manipulated like the input variables; (3) observed variables which are measured by means of sensors and whose values give an indication of the plant performance; (4) controlled variables which are the variables to be regulated; and (5) desired variables which represent the prescribed values of the controlled variables.

5.3 Classification of Control System Types

Control systems can be separated into two fundamental types, open-loop (non-feedback) and closed-loop (feedback). In open-loop systems, the controller generates the manipulated input on the basis of past and present values of the desired input. The system does not measure the controlled variables (a possible inadequacy). Open-loop systems fundamentally rely on conditions staying close to design values. They are often satisfactory if disturbances are not very large, changes in desired values not very severe, and/or performance specifications not very strict (Doebelin, 1985) (see Figure 5.3).

In closed-loop systems, controllers take advantage of the information about the plant that comes with the observed variable (Kwakernaak and Sivan, 1972). An open-loop system can be converted to closed-loop by adding the functions of measurement of the controlled variable and comparison of measured and desired values of the controlled variable (Figure 5.2). Errors between commanded and actual values of the controlled

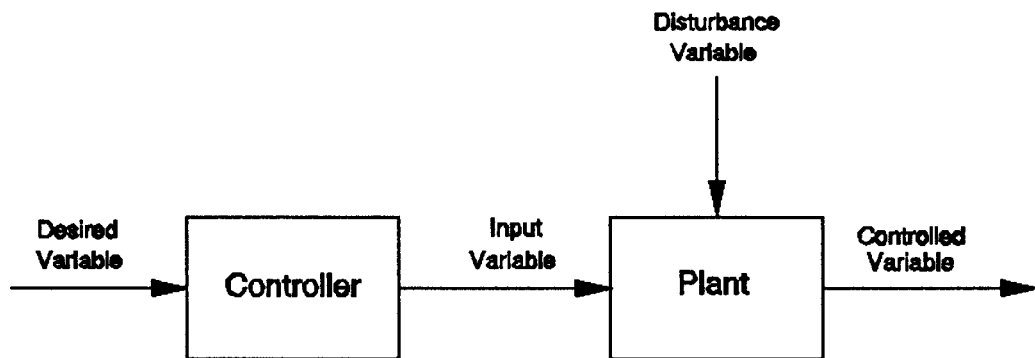


Figure 5.3 Open-Loop Control System

variable will tend to be corrected no matter what their source. This includes errors due to changing commands, system disturbances and disturbances to equipment. The only exceptions are the measurement devices (sensors). If the sensors give wrong information, the feedback will not be able to correct it, thus feedback control depends vitally on accurate measurements (Doebelin, 1985).

5.4 Control of Cable/Lumped-Body Deployment Systems

The expeditious installation of a cable/lumped-body system constitutes a problem in control theory. The control system performs two functions: (1) it estimates the dynamic states of the deployment system to provide the best feedback information for closed-loop control of the system; and (2) it actively controls the dynamic states of the system in real time.

5.4.1 Description of Cable/Lumped-Body Control System

The control system for cable/lumped-body installation can be pictured conceptually as in Figure 5.4. The deployment operation will take place the first time without using the control logic. A new trajectory of the system will be observed because of the deviations caused by the presence of random waves and currents. The observed trajectory is detected and the new body locations are measured and input into the control logic. Then one of the algorithms presented in the following section will be applied on the system to correct the deviations. This will be accomplished by changing the vessel

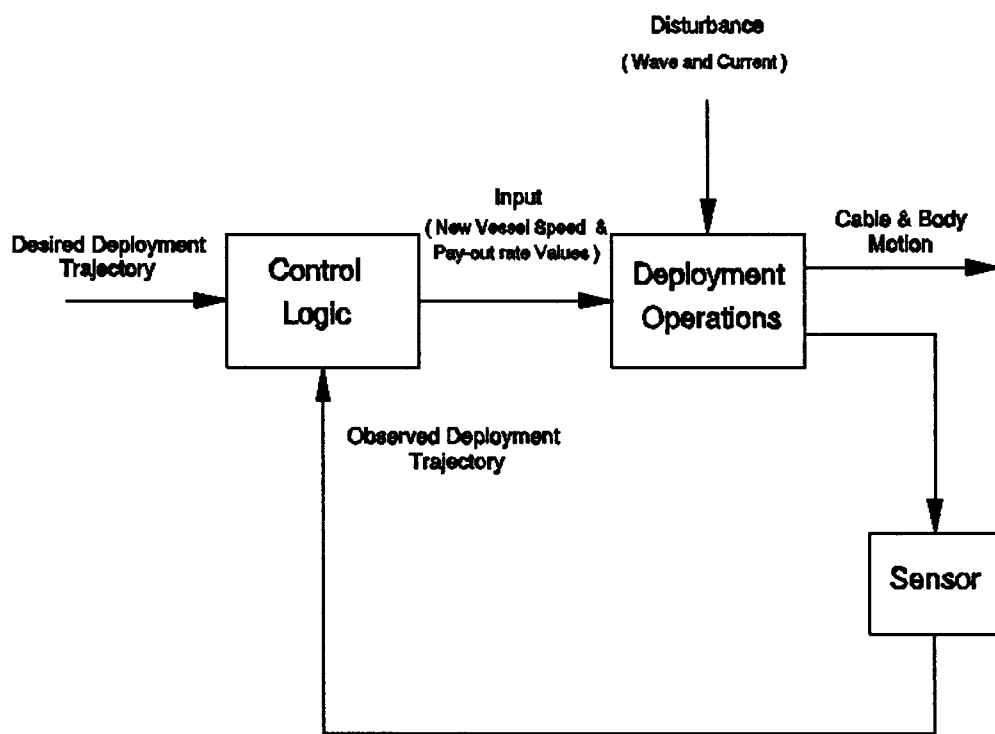


Figure 5.4 Control System for Cable/Lumped-Body Installation

speed and/or the cable pay-out rate values. The new values will be used and new cable and body motions will be observed again.

5.4.2 Control Algorithms

During actual installation, it is anticipated that disturbance (i.e. the uncontrollable input) will cause given deployed lumped bodies to deviate from the intended trajectory predicted by computer simulation. These deviations, if allowed to accumulate, may cause sonar packages to grossly miss the exact target locations. Thus having detected a deviation, some correction in vessel speed and/or pay-out rate is necessary. Three alternative types of algorithms are considered in the control of this system. The classification is based on the controlled parameters.

Control Algorithm 1:

During the control of the cable deployment, the vessel and cable pay-out speeds, v_s and v_c , are modified alternatively at each time step, holding the other variable constant. The decision on which parameter to start the change is arbitrary. The advantage of this algorithm is that it is easy to implement and does not take much computation time.

- Step 1 Initialize the algorithm by using optimum values of vessel and pay-out speeds obtained from optimization search, using mean (deterministic) waves and currents, as initial values $v_s(0)$ and $v_c(0)$, respectively.
- Step 2 Run KBLDYN program for one time step with optimal vessel speed and cable pay-out speed with random waves and currents to determine the new

location of the cable and the lumped bodies.

Step 3

With new locations of vessel and cable/lumped-bodies, and using the current vessel and cable pay-out speed, run KBLDYN program to predict the terminal location of lumped bodies and evaluate the penalty function P using mean (deterministic) waves and currents. The vessel speed is chosen to be changed during this time step and the cable pay-out speed is held constant. So there are two possible modifications that can be applied on the system:

a) Increment vessel speed $(v_s(i+1)=v_s(i)+dv_s)$.

b) Decrement vessel speed $(v_s(i+1)=v_s(i)-dv_s)$.

Evaluate the penalty function in each cases. The vessel speed that minimizes the penalty function is the one to be chosen and implemented on the system.

If both of the incremented and decremented penalty function values are greater or equal to the old value, skip a number of time steps holding the control parameters constant, assuming that the disturbance does not require modifications in the vessel speed.

Then go to step 2.

Otherwise move to the next time step using the new regulated vessel speed and with random waves and currents.

Step 4

With new locations of vessel and cable/lumped-bodies, and using the current vessel and cable pay-out speed, run KBLDYN program to predict

the terminal location of lumped bodies and evaluate the penalty function P using mean (deterministic) waves and currents. The cable pay-out speed is to be modified (if necessary) during this time step and the vessel speed is held constant. So there are two possible modifications that can be applied on the system:

- (a) Increment cable pay-out speed ($v_c(i+1) = v_c(i) + dv_c$).
- (b) Decrement cable pay-out speed ($v_c(i+1) = v_c(i) - dv_c$).

Evaluate the penalty function in each cases. The pay-out speed value that minimizes the penalty function is the one to be chosen and implemented on the system.

If both of the incremented and decremented penalty function values are greater or equal to the old value, skip a number of time steps holding the control parameters constant, assuming that the disturbance does not require modifications in the cable pay-out speed. Then go to step 2.

Otherwise move to the next time step using the new regulated cable pay-out speed and with random waves and currents.

Step 5 Repeat step 2 through 4 of the algorithm until all the sonar packages are placed on the sea floor.

Control Algorithm 2:

In this algorithm, only one variable is to be changed at each time step. This time,

the decision of which variable to be changed is obtained using the penalty function such that the modification that minimizes the penalty function is the one to be adopted. The advantage of this algorithm is that it is more efficient than the previous one.

Step 1 Initialize the algorithm by using optimum values of vessel and pay-out speeds obtained from optimization search, using mean (deterministic) waves and currents, as initial values $v_s(0)$ and $v_c(0)$, respectively.

Step 2 Run KBLDYN program for one time step with optimal vessel speed and cable pay-out speed, with random waves and currents to determine the new location of the cable and the lumped bodies.

Step 3 With new locations of vessel and cable/lumped-bodies, and using the current vessel and cable pay-out speed, run KBLDYN program to predict the terminal location of lumped bodies and evaluate the penalty function P using mean (deterministic) waves and currents. Four possible modifications can be applied on the system:

- (a) Increment vessel speed ($v_s(i+1)=v_s(i)+dv_s$), and hold the pay-out rate constant.
- (b) Decrement vessel speed ($v_s(i+1)=v_s(i)-dv_s$), and hold pay-out rate constant.
- (c) Increment cable pay-out speed ($v_c(i+1)=v_c(i)+dv_c$), and hold vessel speed constant.
- (d) Decrement Cable pay-out speed ($v_c(i+1)=v_c(i)-dv_c$), and hold vessel speed constant.

Evaluate the penalty function in each case. The modification that minimizes the penalty function is the one to be implemented on the system.

If all of the new penalty function values are greater or equal to the old value, skip a number of time steps holding control parameters constant, assuming that the disturbance does not require modifications in the vessel and cable pay-out speed. Then go to step 2.

Otherwise move to the next time step using the new regulated vessel or cable pay-out speed and with random waves and currents.

Step 4 Repeat step 2 through 3 of the algorithm until all the sonar packages are placed on the sea floor.

Control Algorithm 3:

In this algorithm, both controllable variables (vessel speed and cable pay-out rate values) are manipulated simultaneously. The penalty function is used to decide which combination to be implemented on the system to give the best correction. The advantage of this algorithm is that it applies a very accurate control to the system, this becomes important especially when the sonar gets close to the target.

Step 1 Initialize the algorithm by using optimum values of vessel and pay-out speeds obtained from optimization search, using mean (deterministic) waves and currents, as initial values $v_s(0)$ and $v_c(0)$, respectively.

Step 2 Run KBLDYN program for one time step with optimal vessel speed and cable pay-out speed, with random waves and currents to determine the new location of the cable and the lumped bodies.

Step 3 With new locations of vessel and cable/lumped-bodies, and using the current vessel and cable pay-out speed, run KBLDYN program to predict the terminal location of lumped bodies and evaluate the penalty function P using mean (deterministic) waves and currents. Six possible modifications can be applied on the system:

- (a) Increment vessel speed ($v_s(i+1)=v_s(i)+dv_s$), and keep old pay-out speed ($v_p(i+1)=v_p(i)$).
- (b) Increment vessel speed ($v_s(i+1)=v_s(i)+dv_s$), and increment pay-out speed ($v_p(i+1)=v_p(i)+dv_p$).
- (c) Decrement vessel speed ($v_s(i+1)=v_s(i)-dv_s$), and keep old pay-out speed ($v_p(i+1)=v_p(i)$).
- (d) Decrement vessel speed ($v_s(i+1)=v_s(i)-dv_s$), and increment pay-out speed ($v_p(i+1)=v_p(i)+dv_p$).
- (e) Keep old vessel speed ($v_s(i+1)=v_s(i)$), and increment pay-out speed ($v_p(i+1)=v_p(i)+dv_p$).
- (f) Keep old vessel speed ($v_s(i+1)=v_s(i)$), and decrement pay-out speed ($v_p(i+1)=v_p(i)-dv_p$).

Evaluate the penalty function in each case. The modification that minimizes the penalty function is the one to be chosen and implemented

on the system.

If all of the new penalty function values are greater or equal to the old value, skip a number of time steps holding the control parameters constant, assuming that the disturbance does not require modifications in the vessel and cable pay-out speed. Then go to step 2.

Otherwise move to the next time step using the new regulated vessel or cable pay-out speed and with random waves and currents.

Step 4

Repeat step 2 through 3 of the algorithm until all the sonar packages are placed on the sea floor.

CHAPTER 6 SUMMARY AND CONCLUDING REMARKS

6.1 Summary

Optimization procedures and algorithms for cable/lumped-body deployment system have been examined in this study. A computer program based on the optimization algorithms has been developed to perform the search for the optimum controllable values that result in the least possible cost. A methodology and algorithms for the control of the system have been introduced. The main contribution of this study can be summarized as follows:

- 1) Optimization and its corresponding objectives and problem statements are defined. Also some of the optimization methods and techniques were briefly discussed and introduced.
- 2) Optimization methodology and algorithms are developed for optimal design of cable installation technology. Alternating Direction (ADM) and Modified Alternating Direction (MADM) methods are employed.
- 3) The optimization algorithms of the two-dimensional case are implemented on a desk-top computer. The objective of the search is to achieve the optimum vessel speed and cable pay-out rate that result in the minimum penalty value. Once the optimum scenario is predicted, it could be used for the installation.
- 4) Control of dynamic systems and its role is introduced. Three control algorithms are suggested for the control of the installation of the bodies

in deep water. The optimal solution is considered as a predicted solution for real conditions. Thus it is used to guide the control process to account for disturbances caused by currents and waves. The control algorithms are to be applied on the system at every time step.

6.2 Concluding Remarks

During the implementation of the optimization algorithms into computer programs, and during the testing of some examples, some limitations which prevented this study to be more expansive were noticed. These limitations also restricted the implementation of control algorithms into computer programs. Thus the existing program for prediction of cable/lumped-body dynamics (KBLDYN) must be modified to eliminate those limitations in its applications and to include certain features particular to cable installation problems. Some modifications and improvement of KBLDYN program are in progress to facilitate the development of a complete computer-oriented methodology to optimize and actively control the expeditious installation of long serially connected cable/lumped-body systems in deep waters. These modifications can be summarized as follows:

- (1) Because the cable pay-out division depends on the time increment value, and the number of steps per unit length in cable segments, its value was restricted to the minimum value of 0.2 m/sec in most cases. This restriction affected the optimization and gave very small space to the search. For these reasons, KBLDYN program has been changed to admit

smaller values for pay-out division.

- (2) The optimization algorithm developed in chapter 3 is able to complete the optimization of the deployment of any number of bodies. But the early version of KBLDYN program can only finish the optimization of the deployment of just one body. The program has been improved to allow the optimization and control of the deployment of more than one body.
- (3) KBLDYN program is being improved to deal with larger values for vessel speed and cable pay-out rate. Difficulties were noticed when large values were tried.
- (4) In chapter 3, optimization algorithms were developed for two and three-dimensional cases. Only the two-dimensional case is implemented into a computer program. Information concerning the vessel heading are needed to make the three-dimensional case possible where the deployment will take place in a three-dimensional space which is the actual case.

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